DEVELOPMENT AND ENVIRONMENTAL QUALITY: THREE LEVELS OF ANALYSIS

By

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This dissertation examines the link between environmental quality and economic development, exploring the relationship on three different levels. In the second chapter, a model of an investment project involving uncertain environmental effects is developed and the use of research to reduce the uncertainties is explored. Failure to take into account the possibility of improved information via research will bias the decision maker against investment. Market failure, where the social welfare loss from the environmental externality is ignored, leads to no research and over-investment. The optimal social policy in this case involves both a per unit investment tax and an overall project tax.

In the third chapter, potential conflicts between economic growth and environmental degradation are central to the sustainable development debate. An endogenous growth model is used to investigate tradeoffs between economic growth and environmental quality, where growth is dependent on technology improvements, emissions are generated during final goods production, and physical resources can be used to abate pollution. Pollution growth is higher in a decentralized economy, but technology growth rates can not be ranked between the efficient and equilibrium paths. Even with restricted abatement activity, second-best pollution growth will be below the unregulated level. Zero economic growth policies may increase the rate of environmental degradation.

The fourth chapter analyzes international spillovers of a global production-generated pollution externality in a North-South model with endogenously growing economies. When the northern government regulates pollution, gains from trade may be used to enhance environmental quality by increasing pollution abatement. When emissions contribute to a global pollution stock which affects utility, optimal abatement in the North does not depend on the level of emissions in the South and thus unilateral abatement is globally beneficial. For a flow externality however, optimal abatement in the North increases as southern net emissions increase, and a free rider problem may emerge.

CHAPTER 1
DEVELOPMENT AND ENVIRONMENTAL QUALITY

1.1. Introduction

One of the leading questions facing society today is how to balance economic growth and development while maintaining environmental quality and a viable natural resource base. The answers to these questions involve making choices about resource allocations, and economic analysis of these issues can provide insights into solutions to these pressing problems. In this dissertation, I examine several aspects of the economic /environment debate, and each chapter examines a wider scope of economic activity. I first explore a simple, single investment problem where a decision must be made between a development project and preservation of a natural area. For this case, I examine how uncertainty in the environmental outcomes of the development project may be reduced prior to investment to allow for better allocation decisions. Next, I expand the range of analysis to a nation where economic activity which produces polluting emissions conflicts with a desire to maintain environmental quality. Resources must be allocated among activities of economic growth, pollution abatement and consumption. In the final chapter, the scale of inquiry is enlarged further to include transboundary pollution and trade, again in the presence of economic growth. Global environmental problems are increasingly becoming a priority on the international agenda, and an understanding of the interactions of growth, trade and environmental degradation is of increasing interest to both researchers and policy makers.

The remainder of this chapter briefly describes the motivation, scope and main results of each scale of analysis.

1.2. Environmental Research and Investments

Many economic activities have an adverse effect on the environment, although these effects are often at least partially uncertain and may be irreversible (c.f., Arrow and Fisher, 1974; Dasgupta, 1982). The effects of uncertainty and irreversibility on human decisions, and strategies to reduce this uncertainty, have been the focus of considerable study. Two approaches for reducing uncertainty have generally been taken. In the first (Arrow and Fisher, 1974; Fisher and Krutilla, 1985; Dixit and Pindyck, 1994), information arises with the passage of time, and one need merely wait for reduction of uncertainty to arrive with time. For example, by not developing a tract of land, better information about the recreational value of that land will emerge, and thus optimal decisions are initially likely to involve less than full development of the resource. The second information acquisition framework involves a learning by doing, or incremental, investment approach, and in this case development is not necessarily postponed even when it is irreversible (Weitzman *et al.*, 1981; Miller and Lad, 1984). With many environmental uncertainties, however, information is not gained best through experimentation or learning by doing, particularly if there is a long lag between action and a (possibly) irreversible consequence. Research is perhaps the most useful approach for many environmental uncertainties, especially those that are only triggered by human activity, and once triggered are irreversible. Even casual observation suggests that government and private planners are aware that their actions have lasting effects on the environment, and efforts to understand these uncertain interactions are leading to increased expenditures for environmental research.

In Chapter 2, therefore, I examine the use of direct research to reduce uncertainty related to a proposed project or policy which may have irreversible consequences. Because complete elimination of uncertainty is generally infeasible, I determine the optimal research strategy which should be followed before making an irreversible, one-time decision based on updated but still uncertain information. I find that although under certain circumstances the optimal amount of research done may be zero, this conclusion should be arrived at through analysis rather than assumed *a priori*. My results also show that a planner who does not consider the research option will always be biased against investment compared with a planner who recognizes that she can do research to reduce the uncertainty.

The research and investment decisions of a social planner and a private firm will differ, as the social planner takes into account the externality caused by environmental degradation, whereas the firm does not. The firm may invest when it is not socially optimal to do so, and will have a larger than optimal project size. The combination of a per-unit investment tax, a research tax, and a fixed project tax will align the firm's decision to invest and its project size with the social optimum.

1.3. Economic Growth and Pollution Abatement

Although individual project decisions have environmental consequences, national economic growth and its effect on the environment has caused even more conflict and debate between growth advocates and environmentalists. Central to the controversy is how to define and attain a sustainable mix between growth and environmental maintenance. Because a limited amount of resources must be divided between economic growth and environmental maintenance, understanding the interaction between economic growth and degradation is an essential step in delineating national policies for sustainable development.

In Chapter 3 of this dissertation, I explore unregulated and socially optimal trade offs between economic growth and environmental maintenance, and discuss what happens if politically motivated constraints are placed on the allocation of resources or the economic growth rate. In an important departure from previous growth and environment models (Mohtadi and Roe, 1992; Ligthart and van der Ploeg, 1994), I decouple the direct link between pollution and output growth. That is, increases in output due to technological advances do not lead directly to increases in polluting emissions. Empirical studies by Shafik (1994) and Antle and Heidebrink (1995) show in fact that a nonlinear relationship exists between income and environmental amenities, and thus there is not an inescapable link between degradation and growth. However, although technology accumulation is non-polluting in this model, increases in resource inputs (labor and capital) do cause emissions to increase.[1]

Since it is clear that government intervention is necessary for addressing environmental externalities (Shafik, 1994), environmental issues are best represented in an endogenous growth framework where policy prescriptions can affect the balanced growth path (Ligthart and van der Ploeg, 1994; Jones and Manuelli, 1995; Mohtadi, 1996). Thus in this paper, I use an endogenous growth model rather than the usual (in the environmental literature) neoclassical model, as only the former allows for government policy to affect economic growth rates (e.g., Lucas, 1988; Romer, 1986, 1990; Grossman and Helpman, 1991).

Finally, to model empirically relevant trade offs in resource use, this analysis includes a pollution abatement sector. Resources can be used to directly reduce the effects of polluting activity, and empirically we see that abatement activity is an increasingly important part of economic activity.

Results from this analysis indicate that optimal pollution control reduces pollution growth rates, as found by, for example, Tahvonen and Kuuluvainen (1993) and Mohtadi (1996). However, it does not necessarily reduce economic growth, a result found also by Hung *et al.* (1994) in a variety-expansion growth model.

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[1] Because total economic growth will encompass a range of types of growth, development of appropriate policy prescriptions necessitates considering results from specifications where growth is directly linked to pollution as well as this specification.

A positive amount of resources will not always be devoted to pollution abatement, and optimal pollution stock growth may be zero, negative or positive. This result supports the idea that less developed countries who are more tolerant of polluted conditions (and have more pressing poverty problems or better natural assimilative capacities) should be allowed a larger growth rate for the pollution stock while they pursue economic growth. The results also highlight the potential positive role for transfers in pollution abatement technology aimed at reducing the growth rate of pollution in less developed countries.

The sustainable growth rate is higher along the socially optimal path than it is along the equilibrium path, although it is not always positive. Indeed, even when political considerations dictate that no resources be allocated to abatement, pollution growth will still be lower than in the decentralized solution, as the social planner can allocate additional resources to the non-polluting technology sector and less to polluting activities. Lastly, I find that social policies requiring zero economic growth, which some environmentalists believe to be the only way to maintain environmental quality, may actually lead to higher pollution growth rates, as a policy of zero economic growth leads to a constant (never declining) pollution stock.

1.4. Transboundary Pollution and Trade

Although environmental regulations and policy are more typically considered at the local or national level, an increasing number of environmental problems are characterized by geographical spillovers. Thus, appropriate analysis for pollution problems must incorporate transboundary environmental effects, and in the final chapter of this dissertation I widen the scope of analysis to a two-country model with transboundary pollution and trade. A problem of international externalities arises when emissions generated by one country spill over into another, and lacking an international governing board, the affected country can not directly regulate the emissions produced by the polluting country. Understanding the linkages among trade reform, economic growth policy and environmental degradation is crucial for determining what national policies may be appropriate for regulation of international environmental externalities.

Previous research with transboundary spillovers of pollution (Maler, 1990; Hoel, 1991, 1994; Deardorff, 1995) has shown that nationally optimal policies, such as those examined in Chapter 3, will not be globally optimal. Even worse, Hoel (1991) has the distressing result that unilateral reductions in emissions taken by one country may actually lead to increased world emissions as other countries will increase their emissions in response.

Incorporation of economic growth and trade into these models of transboundary pollution has not been done, however. Conversely, environmental models of trade or growth have rarely included transboundary pollution and models with local pollution have indicated that environmental degradation may increase or decrease with trade (Chichilnisky, 1993; Lopez, 1994; Copeland and Taylor, 1994a, 1994b). Chapter 4 therefore examines the effect of increased trade and economic growth on an environmental externality with international spillovers.

The model used is similar to that in Chapter 3, but includes a transboundary pollution spillover, where emissions from two countries affect all consumers in both countries. The countries produce and trade differentiated goods and the North is distinguished in that abatement technology is available, and the government may regulate emissions by imposing a tariff or domestic tax.

Some results obtained here are unique in the environmental literature. Although the South does not use labor in pollution abatement, the relative growth in human capital in the South may be higher or lower than in the North when the North is following optimal policies. Increases in trade that do not affect funding for abatement will unambiguously lead to increased abatement activity in the North; that is, gains from trade are used to improve environmental quality. Even though polluting emissions are generated solely by labor in manufacturing, a single tax on manufacturing labor will not achieve the socially optimal solutions, as emissions induce distortions in both level and growth components in the economy. However, implementation of a manufacturing tax and a tariff on the imported good is sufficient to obtain the first best labor allocations and growth rates for either type of pollution.

The effect of unilateral abatement activity is dependent on whether the environmental externality takes the form of a stock or flow. With a flow pollutant, a free rider problem exists and unilateral reductions may not decrease world pollution.

For stock pollution however, countries do not increase emissions in response to other countries' abatement efforts and overall emissions fall with unilateral reductions.

CHAPTER 2
REDUCING UNCERTAINTY THROUGH BAYESIAN EXPERIMENTATION

2.1. Introduction

We often face the prospect of making decisions when the consequences of our decisions are uncertain or unknown, and one area of economic research has focussed on how to make decisions when complete information is lacking. However, it is rare that decision makers are helplessly caught in the grip of ignorance (Hirshleifer and Riley, 1979). Various contributions to the economic literature on decision making under uncertainty, a number with specific application to environmental problems, explore how information on the uncertain elements may be acquired through the passage of time (Arrow and Fisher, 1974; Fisher and Krutilla, 1985; Dixit and Pindyck, 1994), from sequential investment (Weitzman *et al.*, 1981; Miller and Lad, 1984), or learning by doing (Jovanovic and Nyarko, 1995). Less attention, however, has been directed at the possibility of reducing uncertainty directly by research.[1]

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[1] Swierzbinski and Mendelsohn (1989) explore the effects of accumulating information concerning the size of a backstop technology on the evolution of prices for the currently used nonrenewable resource stock. Dixit and Pindyck (1994) mention, but do not further analyze or discuss, the possibility that the technical uncertainties of a project may be reduced by performing engineering studies.

One area where research may be especially useful is in reducing uncertainty related to the environment. Environmental effects of human decisions are almost always at least partially uncertain (e.g., Arrow and Fisher, 1974; Dasgupta, 1982) and are often irreversible. Damming a river for hydroelectricity production will cause irreversible changes to the surrounding area, but the magnitude and social cost of the effect may be unknown. Therefore, this paper examines the use of research to reduce uncertainty related to a proposed project or policy which may have irreversible environmental consequences.

The effects of uncertainty and irreversibility on environmental decisions, and means for reducing this uncertainty, have been the focus of some economic analysis. Two approaches for reducing uncertainty have generally been taken. In the first (Arrow and Fisher, 1974; Fisher and Krutilla, 1985; Dixit and Pindyck, 1994), information arises with the passage of time, and one need merely wait for resolution or reduction of uncertainty to arrive with time. For example, by not developing a tract of land, better information about the recreational value of that land will emerge. A general result in this literature is that when information is gained over time, optimal first period decisions are less likely to involve full development of the resource. In addition, the presence of irreversibilities leads to lower overall levels of development. The second information acquisition framework involves a learning by doing or incremental investment approach. The possibility of learning more about project costs and benefits as development proceeds makes it more likely that investment in the project will occur (Weitzman *et al.*, 1981). In contrast to the information over time results, when resolution of uncertainty is dependent on some investment activity, optimal first period development is not necessarily more conservative even when development is irreversible (Miller and Lad, 1984). In addition, proceeding with the project for the purpose of providing information as to whether the development is in fact irreversible may also be optimal; that is, an action that does not risk irreversibility may be inferior to strategies that enable a planner to learn whether the irreversibility does exist (Viscusi and Zeckhauser, 1976).

With many environmental uncertainties, however, information is not gained best through experimentation or learning by doing, particularly if there is a long lag between action and a (possibly) irreversible consequence. In addition, waiting and the passage of time will not always lead to more information. Fisher and Krutilla, who themselves use the "waiting" approach, state that in the case of biodiversity values, "relevant information . . . will not come from developing habitats but rather *from research* that, if anything, depends on preserving habitat" (1985, p. 185, emphasis added). Whereas they stop at examining preservation, I explore a third option of using research to reduce uncertainty prior to any investment occurring.[2]

Research activity involves the acquisition of information, which reduces uncertainty and so may improve decisions. However, research requires the expenditure of resources, and complete elimination of uncertainty is generally infeasible. The focus of the present paper is to determine the optimal research strategy which should be followed before making an irreversible, one-time decision based on updated but still uncertain information. I model the research and investment decisions of a social planner and a private firm considering investments in a project in the presence of an environmental uncertainty where research can be used by the decision makers to provide information on the environmental uncertainty. Bayesian updating is used to model improvements in information.

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[2] In fact, an increasing amount of environmental research is currently done to assess the impacts of proposed projects and policies. Many international development agencies now require environmental impact statements prior to initiation of projects. For example, Executive Order 12114, Environmental Effects Abroad of Major Federal Actions, signed by President Carter in 1979 requires an environmental review for all US overseas work, including that done by US AID.

Unlike in the waiting and sequential investment approaches, the first period action in my model is research, not development. Thus, I determine how much research should be done before deciding on the optimal level of investment that will occur in the second period. I discuss how research and investment decisions of a private firm differ from the social optimum, and what policy instruments can be used to align the firm's decisions with the first best.

The remainder of the paper is organized as follows. Section 2.2 outlines the structure of the model. Section 2.3 analyzes the private and socially optimal research and investment decisions, and section 2.4 explores policies for aligning the solutions. Section 2.5 concludes.

2.2. The Model

I assume that a project planner (either a private firm or a social planner) has monopoly rights to an investment project. The project involves an irreversible change in some environmental resource, resulting in a social loss of uncertain magnitude. For example, the project may involve building an oil pipeline or constructing a dam and reservoir, either of which could be detrimental to a natural resource such as biodiversity. I assume that the private returns to the project, the amount of oil or timber which can be obtained in each period of time, are known with certainty for any given project size.[3] Only one decision about the size of the project can be made, and a small open economy is assumed so that output is sold on the international market at a fixed price, q. Future profits are discounted by the interest rate r, and fixed costs of investment, I.[4] Private profits from the project are received indefinitely and are thus given by

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[3] If there were uncertainties as well about private returns for the project, the private firm's decisions on optimal research amount and optimal investment level with regard to this uncertainty would be the same as the social optimal (Byrne 1995). For clarity, I restriction my attention here to uncertainty over the environmental externality.

[4] Constant marginal costs in each period can be thought of as a reduction in q. That is, $q=\alpha-c$ is the net international price, with α as gross international price, and c as fixed marginal costs incurred in each period.

$$\pi = \sum_{t=1}^{\infty} \frac{q\, f(x)}{(1 + r)^t} - I \ ,$$

where $f(x)$ is output dependent on project size x. For simplicity, I assume a concave production function,

$f(x)=ax-bx^2$.

The proposed project has an effect which reduces social welfare. However, the magnitude of the social loss is uncertain and is related to the size of the project. For example, biodiversity loss in an area will be related to the size of the area disturbed, as well as to the probably unknown initial level of biodiversity. I assume that the social loss takes the form,

$$L(k_\epsilon,x) = \begin{cases} 0 & for\ x = 0 \\ gk_\epsilon x + \beta k_\epsilon^2 & for\ x > 0 \end{cases} \ ,$$

where k_ϵ is a random variable representing the unknown environmental parameter. The loss affects welfare in each period and is discounted by a social rate, ρ, which may be different from r. The social loss is an increasing linear function (with slope gk_ϵ) of project size, with an additional component, βk_ϵ^2, which is independent of project size. Loss is increasing in x and therefore is minimized only when no project is undertaken.

The uncertain term describing the environmental parameter is stochastic and given by $k_\epsilon = \gamma + \epsilon$, where $\epsilon \sim N(0,1/s)$.[5] I assume that the planner's prior distribution of γ is normal with mean μ and precision τ. Following Rothschild (1974), μ represents what the planner believes the unknown parameter to be, and τ is how confident she is in her belief. Research can be done to update the prior belief on the uncertain parameter. Investing in research will provide observations, k_i, of the parameter, which are modelled as random draws from a normal distribution[6] with unknown mean γ and known precision s. Research observations on the unknown parameter are assumed to cost R each.

The total social value of the project is

$$\pi_S = \sum_{t=1}^{\infty} \frac{q(ax - bx^2)}{(1 + r)^t} - I - \sum_{t=1}^{\infty} \frac{g k_\epsilon x - \beta k_\epsilon^2}{(1 + \rho)^t} - Rn \quad , \tag{2.1}$$

the private profits minus the social loss and any research costs. The planner will maximize the expected discounted value of the project with respect to project size, x.

The timing of the investment project is as follows. Before the first period, the planner determines whether or not she will invest by considering the expected value of the project based on her beliefs about k_ϵ. A forward looking planner will take into account the potential updating by research when calculating expected project value. If the expected project value is negative, the planner abandons the project at the beginning of the first period. If expected value is positive, the planner determines and carries out the optimal amount of research, taking all observations in the first period. At the beginning of the second period, the planner decides on the optimal size of the project, x, and invests in the project, paying fixed costs I. Production, sales and social welfare loss take place in all periods after that.

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[5] A special case for the uncertain parameter would be where the parameter is nonstochastic and is given solely by γ. In this case, the uncertainty term which describes underlying randomness of the effect (as in equations (2.5) and (2.6) for example), $1/s$, would disappear. If infinite research were possible, the planner could learn the exact value of γ and the uncertainty would be driven to zero.

[6] Assuming that the distribution from which updating observations are taken is known, is convenient and relatively costless assumption, as Rothschild (1974) showed that most updating results change little if the true underlying distribution is assumed to be unknown.

2.3. Investment and Research Decisions

2.3.1 Private Firm's Problem

The firm will not take the social welfare loss into account, and as a consequence, there is no uncertainty in the firm's investment choice or level of investment. (The firm will have no incentive to do research.) If the maximized project value is nonnegative, the firm will invest in the project.

The discounted value of the project to the firm is given by

$$\pi_F = \frac{q}{r}(ax - bx^2) - I \ . \tag{2.2}$$

Maximizing (2.2) with respect to size of project, x, gives the optimal investment level as $x_F^* = a/2b$. Substituting x_F^* into (2.2), the maximized private value of the project is

$$\pi_F{}^* = \max \begin{cases} 0 \\ \dfrac{qa^2}{4rb} - I \end{cases} .$$

The firm will invest if the discount rate is low enough, output high enough, and fixed investment costs not too high. Again, there is no uncertainty, and the firm has an unambiguous invest/not-invest decision.

Investment, however, will entail an external social cost which is not taken into account by the firm, and therefore a market failure exists. Given the optimal investment level of the firm, investment will cause a social environmental loss per period with expected value of $E(L) = (ga/2b)E(k_\epsilon) + \beta E(k_\epsilon^2)$.

2.3.2 Socially Optimal Research and Investment

A socially optimal investment decision will take into account the uncertain environmental externality when deciding on whether to invest and the level of investment. The discounted expected social value of the project is given as

$$E(\pi_S) = \frac{q}{r}\,(ax - bx^2) - I - \frac{1}{\rho}\left(g E(k_\epsilon)x + \beta E(k_\epsilon^2)\right) \tag{2.3}$$

where k_ϵ is unknown, and is subject to the prior beliefs of the social planner.

Proposition 1

The socially optimal project size, x_S^*, will always be smaller than the laissez faire firm's project size, x_F^*.

The socially optimal size of the project will always be the nonnegative x which maximizes (2.3),

$$x_S^* = \begin{cases} 0 \\ \dfrac{a}{2b} - \dfrac{rg}{2bq\rho}E(k_\epsilon) \end{cases}, \tag{2.4}$$

which is less than $x_F^*=a/2b$. If x_S^* is maximized by zero, no investment is done. Otherwise, the expected project value is calculated using (2.4) and (2.3).

2.3.2.1 Decision if Research Is Not Considered

If there were no possibilities for research, or if the social planner does not take into account that she will be able to do research to update beliefs on γ, then the investment decision will be made using the prior beliefs on the mean and variance of the uncertain parameter. Since the social optimum takes into account the environmental cost of the project, we find the following;

Proposition 2

The expected discounted value of a socially optimal project when research is not considered is always less than when the environmental social welfare losses are not considered. Thus, investment is less likely to occur under a social planner who does not consider research than under a firm.

In the absence of environmental research, the investment decision is found by substituting (2.4) into (2.3) directly and using prior beliefs,

$$E(\pi_{S_o}^{*}) = \max \begin{cases} 0 \\ \frac{qa^2}{4rb} - I - \frac{ag}{2b\rho}\mu - \frac{\beta}{\rho}\mu^2 + \frac{g^2 r}{4bq\rho^2}\mu^2 - \frac{\beta}{\rho}\left[\frac{1}{\tau} + \frac{1}{s}\right] \end{cases} . \tag{2.5}$$

The first two terms are the same as for the private firm, and the sum of the remaining terms is negative.

The socially optimal expected value is smaller than the firm's by $(ag/2b\rho)\mu$, the social cost of the loss per unit of project, and $(\beta/\rho)\mu^2$, the loss incurred independent of project size. The positive term captures a mitigating effect on the cost of the externality, since the socially optimal level of investment, x_S^*, will be lower than that for the firm. The final term captures the uncertainty concerning k_ϵ.

2.3.2.2 Optimal Amount of Research

A forward-looking social planner recognizes that research will allow it to use an updated, more accurate belief about the environmental parameter and thus the net social value of the project can be increased by better selection of optimal project size.

After research provides n observations of the uncertain parameter (for example, estimates of biodiversity present in the project area), the expected discounted value of running the project (net of research costs) is found using Bayes theorem (DeGroot, 1970) to update (2.5)

$$\begin{aligned} E(\pi^*_{S_n}) = \frac{qa^2}{4rb} - I - \frac{ga}{2b\rho}\mu' - \frac{\beta}{\rho}(\mu')^2 + \frac{g^2r}{4bq\rho^2}(\mu')^2 \\ - \frac{\beta}{\rho}\left[\frac{1}{\tau+ns} + \frac{1}{s}\right] - Rn \end{aligned} \quad , \qquad (2.6)$$

where

$$\mu' = \frac{\mu\tau + ns\bar{k}}{\tau + ns} \qquad \textit{and} \qquad \bar{k} = \frac{1}{n}\sum_{i=1}^{n} k_i \ .$$

μ' represents the posterior belief on the mean of the uncertain effect, which is a weighted average of the prior belief and observations. As n increases, project uncertainty will decrease, but the effect on project value is ambiguous and depends on the values obtained from research.

Proposition 3

A positive amount of research may be optimal. Assuming an interior solution, optimal research decreases with research costs and confidence in the prior, but is ambiguous with respect to the accuracy of research observations.

Since the amount of research to be done is decided on before any observations are taken, the *unconditional* expectation of project value in (2.6) is maximized to find the optimal number of observations. Because the unconditional value of k_ϵ is μ, the expression for updated μ' collapses to μ, and the only benefit that the firm can expect from research is that uncertainty (term in square brackets) will be reduced. Maximizing the unconditional expected value of (2.6) with respect to n, we obtain

$$n^* = \left[\frac{\beta}{R \rho s} \right]^{1/2} - \frac{\tau}{s} , \tag{2.7}$$

which is positive for $\beta s > \tau^2 R\rho$ (Figure 2.1). Second order conditions will always be satisfied.

The number of observations will increase as the cost of research and the confidence in the prior decrease. The higher the social discount rate, the less likely it is that any research will be done, as future environmental losses carry less weight.

The precision of research observations, s, has an ambiguous effect on the optimal number of observations (Figure 2.2). When the accuracy of research is small relative to the planner's confidence in his prior belief, τ (over the range of $\beta s < \tau^2 R\rho$), the updated belief on the environmental externality will very closely resemble the prior, and it is not optimal to do research. As s increases through the range of $\tau^2 R\rho < \beta s < 4\tau^2 R\rho$, new observations have greater weight and are more worthwhile to collect; thus n is increasing in s. For even higher values of s, the accuracy of research is sufficiently great that the same updating can be obtained with fewer observations, and optimal n falls as research accuracy continues to improve.

2.3.2.3 Investment Decision with Research

When the social planner takes into account the possibility of doing research, the expected value of running the project will incorporate the optimal number of observations, the effect of research on the uncertainty terms, and the cost of research.

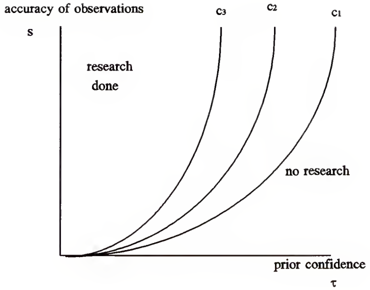

Figure 2.1 Likelihood of Undertaking Research, $c_1 < c_2 < c_3$

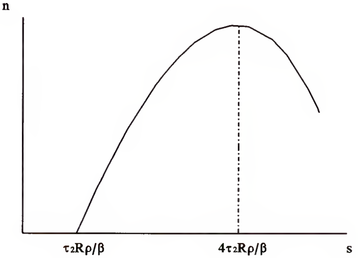

Figure 2.2 Optimal Number of Observations

Proposition 4

When optimal research is done, the expected project value is higher and investment is more likely than if no research were done.

The total expected value of running the project is found by substituting (2.7) into the unconditional expected value of (2.6) and subtracting research costs. The investment decision will be based on

$$\begin{aligned} E[\pi_{S_n}{}^{*}] = {} & \frac{qa^2}{4rb} - I - \frac{ga}{2b\rho}\mu + \frac{g^2r}{4bq\rho^2}\mu^2 - \frac{\beta}{\rho}\left[\mu^2 + \frac{1}{s}\right] \\ & - \left(\frac{\beta R}{\rho s}\right)^{1/2} - \left[\left(\frac{\beta R}{\rho s}\right)^{1/2} - \frac{R\tau}{s}\right] \end{aligned} \tag{2.8}$$

if $n^{*}>0$. If $n^{*}=0$, the investment decision will be the same as the no research investment decision (2.5). The final term is the total cost of doing the optimal amount of research (Rn^{*}). With $n^{*}>0$, this term is always positive.

With research, the socially optimal value of running the project will always be at least as large as the value when research is not considered, as observations will only be taken when doing so increases the expected value of the project, and the number of observations can always be set to zero, reducing the investment decision (2.8) to that in (2.5). Thus, the planner who does not consider research will be biased against investment. This result concurs with previous conclusions in Dixit and Pindyck (1994) that disregarding the possibility of improved information arriving over time will bias a decision maker against investment. The result here is even stronger since information acquisition has a direct cost.

Comparative statics on the value of running the project can be found by direct differentiation of (2.8). Increases in research cost, R, change the expected value of the project in two ways. As the cost of each observation increases, fewer observations are taken, uncertainty is reduced less, and project value falls. On the other hand, the effect on total research cost is ambiguous, since increasing cost decreases the optimal number of observations. Overall, however, increasing research cost will always decrease expected project value.

The expected value of running the project increases as the accuracy of research on the uncertain parameter increases, although again with two separate effects. First, increasing precision of observations will decrease the uncertainty terms in (2.8) and so increase project value. However, because the number of observations is ambiguous with respect to s, increasing research accuracy may increase or decrease total costs of research.

2.3.2.4 Socially Optimal Level of Investment

If the socially optimal decision is to invest, then at the beginning of the second period the planner will calculate the optimal project size, x^*_S, based on (2.4). If research optimally is not done, $n^*=0$, the prior belief on γ is used for the expected value of k_ϵ, and the level of investment is given by

$$x_{s_o}^* = \frac{a}{2b} - \frac{rg}{2bq\rho}\mu \ . \tag{2.9}$$

If research is done, the posterior belief on γ will be used for $E(k_c)$, and using (2.7) for the optimal number of observations, we obtain

$$x_{s_n}{}^{*} = \frac{a}{2b} - \frac{rg}{2bq\rho}\left[\bar{k} + \tau(\mu - \bar{k})\left[\frac{R\rho}{\beta s}\right]^{1/2}\right] . \tag{2.10}$$

The project size in (2.10) includes a weighted average of the prior belief and of values from research observations. If the research does not give accurate results (s small), then less weight is put on observed values, especially if the planner has a lot of confidence in its prior belief (τ high). Also, the weight on the prior mean increases with cost of research (R) and with the social discount rate (ρ). If the prior mean is lower (higher) than the average observations, the second part of the term in brackets is negative (positive), and will cause the updated beliefs to be lower (higher) than observed values for conversion.

Not surprisingly, the environmental loss which occurs with investment will always be less under the socially optimal project size.

2.4. Socially Optimal Policies

Because the private firm does not take the environmental externality into account, it has incentives to invest when it is not socially optimal to do so, and will invest at a higher level then is socially optimal.[7] Thus, a social policy should affect project value so that the firm will only invest in circumstances when it is socially optimal to do so, and should reduce the firm's project size.

Proposition 5

A two part tax is necessary to align the firm's investment decision with the no research social optimum. A third tax component is required if the socially optimal amount of research is to be done.

A per-unit investment tax leads to a project size for the firm of $x^*_F = (a/2b) - (tr/2bq)$, where t is the per unit tax on investment. If no research is done, the project size is socially optimal for $t^* = (g\mu/\rho)$ where μ is the social prior belief on the uncertain parameter. In addition, a fixed investment tax of

$$T = -\frac{\beta}{\rho}\left[\mu^2 + \frac{1}{\tau} + \frac{1}{s}\right] \tag{2.11}$$

will cause the firm to invest in the project only when it is socially optimal to do so.

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[7] This result comes from the fact that investment is irreversible and thus the environmental effect always is a social loss. If investment, for example conversion of rainforest for plantation, were reversible, then investment level (area converted) could potentially take on a negative value. Then, if the social benefit of biodiversity outweighed the gain from plantation profit, the social planner would invest in a project that reverts existing plantation land back to rainforest. The firm would realize no private gain from such reversion, and so never undertake it.

If the social optimal involves research, the firm will pay the costs of research which are known ahead of time to both the social planner and the firm. The optimal number of observations are as in (2.7), and thus total research costs,

$$Rn^* = \left[\frac{R\beta}{\rho s}\right]^{1/2} - \frac{\tau R}{s} \quad ,$$

will be an additional up front fixed cost (tax) on the firm. With research, the optimal fixed tax and tax per unit investment will depend on the updated belief about the uncertain parameter. The expected variable taxes will be the same with updating, as the expected value of the updated parameter is the same as the prior value. The fixed tax, however, will have the uncertainty terms reduced as an expected result. Thus, doing research will lower the expected fixed tax by reducing $1/\tau$ in (2.11).

The intuition behind these taxes is straightforward. The variable tax is similar to a Pigouvian tax, and is equal to the belief about how much social loss will occur with each unit of investment. The optimal fixed tax is simply the discounted sum of the loss that will occur with any level of investment and the uncertainty over the environmental parameter. This uncertainty, and thus the fixed tax, is reduced when research is done, but the research costs are included as an additional tax.

2.5. Conclusions

Decisions are generally made under some degree of uncertainty. However, many situations offer the possibility of gaining more information either by waiting, by trial and error, or by direct research on the uncertainty. Research is perhaps the most useful approach for many environmental uncertainties, especially those that are only triggered by human activity, and once triggered are irreversible. Although under certain circumstances the optimal amount of research may be zero, this conclusion should be arrived at by analysis rather than assumed *a priori*.

Planners and decision makers are aware that their actions have lasting uncertain effects on the environment, and that consequences of their actions will be affected by environmental uncertainties. Efforts by governments and private companies to understand these uncertain interactions are leading to increased expenditures for environmental research. As this paper demonstrates, guidelines for optimal research strategies can be arrived at from economic analysis, allowing a more efficient allocation of research effort than is gained in the current, often *ad hoc*, research funding methods.

This paper has examined a specific situation where an investment project involves an uncertain environmental effect, and research may be done to gain more information about this effect. A planner who does not consider the research option will always be biased against investment compared with a planner who recognizes that she can do research to reduce the uncertainty. The firm will invest when it is not socially optimal to do so, and will have a larger than optimal project size. Interestingly, the accuracy level of research has an ambiguous effect on the optimal amount of research done. The combination of a per-unit investment tax, a research tax, and a fixed project tax will align the firm's decision to invest and project size with the social optimum.

This analysis considered the restrictive case where the investment decision had to be made prior to any research being done. Thus, research could only be used to determine the optimal project size. A simpler framework may allow for research being done prior to the investment decision, so that updating affects the decision to invest, as well as the level of investment.

There are several other extensions that can be taken from this analysis. A static approach was used here, where the optimal amount of research was determined before any research was done. While this may fit many empirical situations, it is more efficient to allow optimal research amounts to vary depending on the observations obtained; that is, to have a dynamic research strategy. Also, the social policy analysis presented here assumes that the social planner and the firm share both information and prior beliefs. Empirically, it is likely that beliefs will differ and that information gained from research done by one party will not be perfectly known by the other. Thus, cases where there is asymmetric information about environmental uncertainties should also be examined, and relevant social policies derived.

CHAPTER 3
IS GROWTH A DIRTY WORD? POLLUTION, ABATEMENT AND ENDOGENOUS GROWTH

3.1. Introduction

Sustainable development[1] has become a catch phrase in environmental and economic circles. However, what are considered to be potentially sustainable paths may vary greatly. At one end of the spectrum is the view that greater economic activity inevitably leads to environmental degradation and ultimately economic collapse; thus the only sustainable path is one of no economic growth. At the other extreme is the belief that those environmental problems worth solving will be addressed automatically as economic growth proceeds. Most likely, however, the path for sustainable development lies somewhere between these extremes.

Investigating the interaction between economic growth and environmental degradation is an essential step in delineating possibilities and plans for sustainable development. I use instantaneous utility growth--defined as a combination of economic growth and environmental maintenance--as an index of sustainable growth, and explore both decentralized (equilibrium) and socially optimal (efficient) growth paths. Additionally, I discuss what happens if politically motivated constraints are placed on the allocation of resources or the economic growth rate. I use a three-sector endogenous growth model which has technology/human capital accumulation as the engine of growth. In an important departure from previous growth and environmental models, I decouple the direct link between pollution and output growth[2] by having increases in output due to technological advances not leading directly to increases in polluting emissions. In this model, economic growth affects consumer utility via consumption levels, and emissions affect consumers directly via disutility from a pollution stock.

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[1] Most definitions follow the tenor of the World Commission on the Environment and Development (The Brundtland Report, 1987) in describing sustainable development as a system having the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs.

This paper makes three important contributions to the literature on growth and the environment. First, the model extends the recent use of endogenous growth models incorporating environmental externalities. Neoclassical growth models have been used extensively to examine the link between environmental degradation and economic growth (e.g., Barrett, 1992; Tahvonen and Kuuluvainen, 1993; John and Pecchenino, 1994; and see Pezzey, 1989, for a survey of earlier work). Generally, the presence of environmental externalities results in lower consumption and lower physical capital accumulation when pollution is optimally controlled. However, using these models to develop policy guidelines which align the decentralized with the efficient path is problematic, as long-run growth paths in the neoclassical models are not affected by policy variables. Recent advances in growth theory do provide a policy link for affecting growth rates, and much current work in economic growth focusses on endogenous growth models where a non-zero long-run rate of economic growth is a function of choice variables (e.g., Lucas, 1988; Romer, 1986, 1990; Grossman and Helpman, 1991). These models have only recently begun to be exploited for analyzing environmental questions (Ligthart and van der Ploeg, 1994; Bovenberg and Smulders, 1995; Jones and Manuelli, 1995; Mohtadi, 1996). Since it is clear that government intervention is necessary for addressing environmental externalities (Shafik, 1994), environmental issues are usefully modelled in an endogenous growth framework where policy prescriptions affecting the balanced growth path are available.

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[2] Empirical studies have shown that the link between economic growth and environmental degradation is by no means straightforward. Different environmental problems are more pronounced in lower or higher income countries and some pollutants show an inverted U-shaped relationship with per capita income (Grossman and Krueger, 1993; Shafik, 1994; Antle and Heidebrink, 1995).

The second major contribution lies in the specification of the pollution-generating process. Many previous papers have assumed that pollution is directly increasing with any increase in final goods output or in consumption (e.g., Mohtadi and Roe, 1992; Ligthart and van der Ploeg, 1994; Mohtadi, 1996). However, empirical evidence (Shafik, 1994; Antle and Heidebrink, 1995) shows a nonlinear relationship between income and environmental amenities, and thus an inescapable link between environmental degradation and growth does not always exist. It is not clear, for example, that the accumulation of human capital as in Lucas (1988) should always be a "dirty" process. If the human capital acquired was how to catch fish more efficiently through the use of better designed nets, pollution from fossil fuels used in powering the boat would not need to increase, nor would oil slicks left by the boat on the water become larger. Likewise, technological advances that increase the efficiency of a productive process or increase the quality of goods produced will not always (or even often) lead to increased pollution, yet both are considered as economic growth.

Clearly, not all increases in productivity are pollution neutral. For example, technological change may necessitate an increase in complementary pollution-causing capital. In the model presented here, technology accumulation is non-polluting, but increases in resource inputs (labor and capital) do cause emissions to increase. This specification allows for growth and pollution tradeoffs which are appropriate for some types of pollution. The model does not represent all forms of economic growth, as growth may be directly pollution increasing in some (or many) cases. However, because total economic growth will encompass a range of types of growth, development of appropriate policy prescriptions necessitates considering results from this specification as well as from specifications where growth is directly linked to pollution.

The final contribution in this paper comes from the inclusion of a pollution abatement sector. In many models, pollution stocks can only lessened by an exogenous assimilative or regenerative capacity of the environment, or by a reduction in the polluting activity. Here however, resources can be used to directly reduce the effects of polluting activity. Pollution abatement may show a "J-curve" of increasing activity with increased income levels, both empirically and theoretically (Selden and

Song, 1995), and thus may play an important role in regulation of pollutants. The inclusion of an explicit abatement sector allows for a realistic greater flexibility in tradeoffs between production and environmental degradation.

I find that optimal pollution control reduces pollution growth rates, similar to previous results (Mohtadi and Roe, 1992; Tahvonen and Kuuluvainen, 1993; Mohtadi, 1996). However, as found by Keeler *et al.* (1974), the optimal solution does not always involve a positive amount of resources devoted to pollution abatement. Unlike these papers, however, pollution control does not necessarily reduce economic growth, a result found also by Hung *et al.* (1994) in a variety-expansion growth model. Economic and pollution growth rates are not restricted to a strict one to one correspondence and the growth rate of the pollution stock may be positive or negative. This contrasts with previous results where the pollution stock is linked to output and always has a non-negative growth rate.

The first-best optimal rate of sustainable growth, which we can also think of as a measure of "standard of living" growth, is higher along the efficient than along the equilibrium path, although not always positive. When political considerations dictate that no resources be allocated to abatement, pollution growth will still be lower than in the decentralized solution, as the social planner can allocate additional resources to the non-polluting technology sector and less to polluting activities. Finally, I find that social policies requiring zero economic growth may actually lead to higher pollution growth rates.

The remainder of this paper is organized as follows. Section 3.2 describes the basic model, and section 3.3 solves for the decentralized (equilibrium) growth path and resource allocations. Section 3.4 considers the first-best social planner's (efficient) solution, and section 3.5 discusses what happens when society commits itself to a) a restriction on labor in pollution abatement, or b) a policy of zero economic growth. Section 3.6 concludes.

3.2. The Model

I use a simple three-sector model where labor can be allocated to manufacturing (which is pollution increasing), technology accumulation (pollution neutral), or emissions abatement (pollution reducing). Similarly, capital can be used in activities which are pollution increasing (manufacturing) or pollution decreasing (abatement). Both labor and capital are assumed to be perfectly and costlessly mobile among sectors. Innovation leads to improvements in an input to production. This input can be thought of as a combination of human capital and/or technology, but will mainly be referred to as technology. Growth in the technology level is a linear function of labor devoted its accumulation

$$\dot{A}(t) = A(t)\delta L_A \quad . \tag{3.1}$$

L_A is the labor devoted to the technology (growth) sector, $A(t)$ is the current level of technology used in manufacturing, and δ is a productivity parameter. It is assumed that there is no depreciation of technology.

The technology input is combined with labor and capital in manufacturing, L_M and K_M, to produce a single final good, *y(t)*. A Cobb-Douglas relationship exists between labor and capital in the final goods production function. Letting consumption be denoted *c(t)*, I assume that all output is consumed at each point in time,

$$y(t) = c(t) = A(t)L_M^{\alpha}K_M^{1-\alpha} \quad . \tag{3.2}$$

This structure has no technological spillovers (c.f. Jones and Manuelli, 1995), and thus highlights the effect of the pollution externality. Without an environmental externality, the competitive equilibrium will be optimal and display growth; any divergences between the efficient and equilibrium paths are therefore due to the environmental externality.

Emissions are generated during final goods production and are caused by both labor and capital in manufacturing. Emissions can be reduced by a pollution abatement activity which uses capital and labor and takes a Cobb-Douglas functional form. The evolution of pollution stock, *z(t)*, takes the following form,

$$\dot{z}(t) = [\phi_1 L_M + \phi_2 K_M - \gamma L_Z^{\sigma}K_Z^{1-\sigma}]z(t) \quad . \tag{3.3}$$

Evolution of the pollution stock (3.3) differs from models where emissions are assumed to be proportional to total goods produced, that is, where increases in any input necessarily raise emissions levels. In (3.3), emissions rise when the labor or capital used in manufacturing increases, but not when the technology level increases.[3] ϕ_1 and ϕ_2 are measures of how dirty the manufacturing process is for the final good. By varying these parameters, we can specify more or less polluting industries, and distinguish between industries where additional labor is more polluting and those where capital is more polluting. Emissions can be reduced by devoting labor and capital to abatement. γ is a measure of the effectiveness of the abatement process, and can be thought of as a fixed level of abatement technology.

Net emissions at any time are thus given by the expression in square brackets in equation (3.3). The incorporation of emissions into the pollution stock is dependent on the current stock level, *z(t)*. When the pollution stock is small, many types of pollutants are more readily dissipated by the natural assimilative capacity of the earth than when higher pollution stocks are present.[4] In addition, for a number

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[3] However, because there are technological advances which *will* cause pollution to increase as productivity increases, I compare my results at various points in this paper to a similar model where increases in human capital do increase emissions. For the comparative analysis, I assume a simpler Ricardian model ($\alpha=1$) and specify the evolution of pollution stock as

$$\dot{z}(t) = \phi A(t) L_M - \gamma L_Z z(t) \quad ,$$

where emissions, $\phi A(t) L_M$, are generated by total output. All increases in production, whether due to increases in manufacturing labor or increases in technology levels, will raise emissions. These two models may be thought of as characterizing non-polluting and polluting technology improvements. In this model, even with pollution abatement as an activity option, there is a fixed relationship between output growth and pollution stock increases. Empirically, economic growth in an economy is likely to be composed of both polluting and non-polluting growth, and thus policy guidelines must be applied based on the type of technology advances occurring in the industry being targeted.

[4] This characterization is similar to Bovenberg and Smulders (1995), where the regenerative process of a renewable natural resource is dependent on the level of

of pollutants, for example atmospheric ozone, reactions among pollutant particles are dependent on the concentration of particles, and it is these reactions which are environmentally detrimental.

The intertemporal utility of a representative agent is defined as

$$U = \int_0^\infty e^{-\rho t} \ln V(t)\, dt \quad , \tag{3.4}$$

where $\rho > 0$ is the constant subjective discount rate. *V(t)* is the instantaneous subutility function which depends on the levels of consumption and of the pollution stock, and takes the following Cobb-Douglas form,

$$V(t) = c(t)\ z(t)^{-\epsilon} \quad . \tag{3.5}$$

ϵ is a positive constant representing the relative (dis)utility of pollution and consumption.

A natural definition of sustainable growth[5] in the context of this model is the long-run rate of growth of instantaneous utility, which encompasses changes in the growth rates of both consumption and the pollution stock,

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resource stock.

[5] There is no one accepted definition of sustainable growth, although the Brundtland report is perhaps the most widely cited. Munasinghe and McNeely (1995) provide an overview of definitions and approaches.

$$g_V = \frac{\dot{V}}{V} = \frac{\dot{c}(t)}{c(t)} - \epsilon \frac{\dot{z}(t)}{z(t)} \quad . \tag{3.6}$$

Equation (3.6) states that sustainable growth is affected positively by growth in consumption and negatively by growth in pollution stock. The value of ϵ is likely to differ among countries, and will directly affect the sustainable growth path. From (3.2) we can show that consumption grows at the same rate as technology, and thus (3.6) indicates the interaction between economic growth and pollution growth.[6]

3.3. Equilibrium Solution

I assume the existence of an infinite number of consumer-producer households in the economy. Each household i is endowed with L_i units of labor and K_i units of

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[6] An alternative representation of social welfare is the total utility accruing to individuals over time,

$$U = \int_0^\infty e^{-\rho t} \left[\ln c(t) - \epsilon \ln z(t) \right] dt \quad .$$

The growth rates of consumption and pollution, which I denote g_A and g_Z to be consistent with later notation, are values which can be solved for in the decentralized and social planner's problems. Integrating the above expression from time zero to infinity, we obtain

$$U = \frac{1}{\rho} \left[\ln c(0) - \epsilon \ln z(0) + \frac{g_A - \epsilon g_Z}{\rho} \right] \quad ,$$

where c(0) and z(0) are initial levels of consumption and pollution respectively. If these values are normalized to one, we see that this measure of social welfare is directly proportional to the above definition of sustained growth, justifying (6) as a reasonable measure of both welfare and sustainable growth.

capital. Since pollution is a negative externality, agents will take the pollution stock as given and have no incentive to supply labor or capital for emissions reduction. Thus, without intervention, $L_Z = K_Z = 0$, and no pollution abatement will be undertaken. Individuals maximize

$$U_i = \int_0^{\infty} e^{-\rho t}[\ln c_i(t) - \epsilon \ln \bar{z}(t)]dt \tag{3.7}$$

subject to

$$c_i(t) = y_i(t) = A_i(t) L_{M_i}^{\alpha} K_{M_i}^{1-\alpha} \quad , \tag{3.8}$$

$$\dot{A}_i(t) = A_i(t) \delta L_{A_i} \quad , \tag{3.9}$$

and

$$L_i = L_{A_i} + L_{M_i} \qquad and \qquad K_i = K_{M_i} \quad . \tag{3.10}$$

$\bar{z}(t)$ is the aggregate level of pollution. Equations in (3.10) show that labor will be divided between manufacturing and technology improvement, and all capital will be used in manufacturing.

Emissions are unabated and thus growth of the pollution stock is always positive,

$$\dot{z}(t) = \left[\phi_1 \sum_{i=1} L_{M_i} + \phi_2 \sum_{i=1} K_{M_i}\right] \bar{z}(t) \quad . \tag{3.11}$$

Emissions depend on the aggregate capital endowment and on the total labor devoted to manufacturing in the economy. For comparison with the efficient balanced growth path, I assume all individuals are identical and present the society-wide totals for labor allocations and growth rates.

Proposition 1:

At the solution to the decentralized problem, the total allocation of labor in the economy to final goods production, $L_M{}^{\circ}$*, the growth rate of technology,* $g_A{}^{\circ}$*, the growth rate of pollution,* $g_Z{}^{\circ}$*, and the sustainable growth rate of the society,* $g_V{}^{\circ}$*, are all constant and given by:*

$$L_M{}^{\circ} = \frac{\alpha\rho}{\delta} \quad , \tag{3.12}$$

$$g_A{}^{\circ} = L\delta - \alpha\rho \quad , \tag{3.13}$$

$$g_Z{}^{\circ} = \frac{\phi_1\alpha\rho}{\delta} + \phi_2 K \quad , \tag{3.14}$$

and

$$g_V{}^{\circ} = L\delta - \rho\alpha - \epsilon\phi_2 K - \frac{\rho\alpha\epsilon\phi_1}{\delta} \quad . \tag{3.15}$$

Proof: See Appendix A.1.

The allocation of labor in the decentralized solution can be depicted graphically (Figure 3.1). $L_M{}^{\circ}$ is constant at $\alpha\rho/\delta$, and $L_A{}^{\circ}$ is found at the intersection

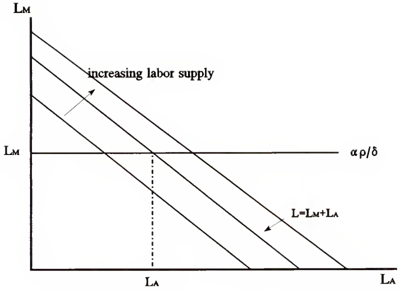

Figure 3.1 Decentralized Equilibrium Labor Allocations

of the L_M locus and the full labor employment constraint. An increase in the importance of current consumption or in the marginal product of labor in final goods production causes agents to devote more labor to manufacturing and less to technology improvements. If labor endowments are below $\alpha\rho/\delta$, all labor will be devoted to manufacturing.

Changes in the endowments of capital and labor have different effects on the decentralized economy's utility growth. All capital is used in manufacturing, and so as capital increases, emissions and pollution growth rates unambiguously increase and utility growth decreases. Total output and consumption at any point in time will also increase with K, but this is a level effect, and does not affect the rate of growth of final goods production. On the other hand, all increases in labor are allocated to technology accumulation, and thus are utility growth improving. Because no abatement is done, increases in per unit emissions from either manufacturing labor or capital (ϕ_1 or ϕ_2) will increase the rate of growth of the pollution stock.

The growth rate of the pollution stock is always positive, and a positive rate of growth in utility (standard of living) is only possible if

$$\delta^2 L > \delta\epsilon\phi_2 K + \rho\alpha(\delta + \epsilon\phi_1) \quad .$$

If L is small or the capital endowment large, the negative effect of pollution stock growth (driven by manufacturing activity) will dominate the positive growth from technology improvements. In this case, the standard of living measure declines over time, and consumers become progressively worse off. For a larger labor supply, growth from technology accumulation can outweigh the disutility of pollution growth, and a positive sustainable growth rate is possible. Reductions in the discount rate ρ or increases in the productivity of the technology sector will decrease L_M and increase L_A, increasing the chance that the sustainable growth rate is positive. For a given labor endowment, low productivity of the technology sector, very dirty manufacturing processes, or a high level of pollution disutility make positive sustainable growth less likely.[7]

The sustainable growth rate (3.15) may be positive or negative. A negative growth rate implies that instantaneous utility will approach zero over time.

It is clear from (3.13) and (3.14) that the growth rates of technology and pollution are affected differently by economic parameters, and therefore we get:

Lemma 1:

The growth rate of pollution is not a function of the technology growth rate; also the converse.

Proof: See Appendix A.1.

There is not a one to one correspondence between pollution and economic growth rates; that is, changes in any model parameter will have differential effects on the two growth rates. This result, unusual in the literature and holding throughout, comes from the evolution of pollution stock (3.3) which decouples emissions from the engine of growth. In contrast, when emissions are generated by total output, growth in pollution can always be written as a function of economic growth, even in the presence of abatement. For example, with the specification of polluting technology growth in footnote 3, pollution stock will always grow at the same rate as technology improvements and consumption. In that case, the growth rate of utility is positive only if $\epsilon < 1$. The result in Lemma 1 holds along the efficient (first best) path as well as the equilibrium path.

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[7] The decentralized results for this model are very similar to those found for the simplified polluting technology growth model set out in footnote 3. There, all labor will again be split between manufacturing and technology growth, $L_M=\rho/\delta$ and $L_A=L-\rho/\delta$. This result comes from the fact that households do not take into account the environmental externality and labor allocation decisions are the same, regardless of the source of polluting emissions.

Transition dynamics to the balanced growth paths, for this and all other solutions discussed in the paper, are quite straightforward. Labor and capital allocations are choice variables and will jump to their steady-state levels. Since growth rates in technology and pollution depend only on these allocations, growth rates will similarly jump to their balanced steady-state paths.

3.4. Efficient (First-best) Solution

The social planner will allocate labor among three activities: manufacturing, technology improvements, and pollution abatement; and capital between manufacturing and abatement, to maximize an intertemporal utility function,

$$U = \int_0^\infty e^{-\rho t}[\ln c(t) - \epsilon \ln z(t)]dt \tag{3.16}$$

subject to

$$c(t) = y(t) = A(t)L_M^\alpha K_M^{1-\alpha} \quad , \tag{3.17}$$

$$\dot{A}(t) = A(t)\delta L_A \quad , \tag{3.18}$$

$$\dot{z}(t) = [\phi_1 L_M + \phi_2 K_M - \gamma L_Z^\sigma K_M^{1-\sigma}]\, z(t) \quad , \tag{3.19}$$

and

$$L = L_M + L_A + L_Z \qquad \textit{and} \qquad K = K_M + K_Z \quad . \tag{3.20}$$

As in the decentralized solution, all output from production (3.17) is consumed, and the evolution of technology (3.18) depends on the amount of labor devoted to its accumulation. The social planner internalizes the environmental externality, *z(t)*, and allocates resources to affect the pollution growth rate (3.19). Full employment conditions for the economy are given in (3.20).

Proposition 2:

In the efficient (first best) solution, labor and capital may be allocated to abatement, and less of both are allocated to final goods production than in the decentralized solution. Net emissions and growth of the pollution stock are reduced *below the equilibrium level. The technology growth rate, however, can not be ranked against the equilibrium growth rate.*

Proof: See Appendix A.2.

In the social planner's solution, manufacturing is the only sector where labor and capital allocations are necessarily non-zero,

$$L_M^* = \frac{\rho\alpha}{\delta} - \frac{\rho\alpha\epsilon\phi_1}{\delta(\delta + \epsilon\phi_1)} \qquad \text{and} \tag{3.21}$$

$$K_M^* = \frac{\rho(1-\alpha)}{\epsilon[\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}]} \tag{3.22}$$

where

$$G = \frac{\epsilon\sigma\gamma}{\delta} \quad .$$

Comparing (3.21) to the equilibrium level of labor in manufacturing (3.12), the first-best allocation to manufacturing is lower by a term reflecting optimal compensation for the environmental externality. As the relative disutility of pollution falls, manufacturing labor rises to the equilibrium level. Manufacturing capital is decreasing in ϵ, and thus as ϵ approaches zero the capital in manufacturing increases until all capital is allocated to final goods production.

A non-negative amount of labor and capital may be allocated to abatement:

$$L_Z^* = KG^{1/1-\sigma} - \frac{\rho(1-\alpha)G^{1/1-\sigma}}{\epsilon[\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}]} \qquad \textit{and} \tag{3.23}$$

$$K_Z^* = K - \frac{\rho(1-\alpha)}{\epsilon[\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}]} \quad . \tag{3.24}$$

Capital and labor in abatement are increasing in the relative disutility of pollution, and decreasing in the discount rate, the opposite of what occurs in manufacturing allocations. Increases in emissions per unit capital in manufacturing, ϕ_2, will increase allocations of both labor and capital to abatement. However, labor and capital will be devoted to pollution abatement only if

$$K \geq \frac{\rho(1-\alpha)}{\epsilon[\phi_2 + \gamma(1-\sigma)G^{\sigma/(1-\sigma)}]} \quad .$$

If the initial capital stock is small, and manufacturing is not "very" polluting, then no abatement activity will be undertaken. Higher productivity of abatement activity, γ, will make abatement more likely, as well as increasing the amount done.

The technology growth rate is given by

$$g_A^* = \delta L - \rho\alpha + \frac{\rho\alpha\epsilon\phi_1}{\delta + \epsilon\phi_1} - \delta K G^{1/1-\sigma} + \frac{\delta\rho(1-\alpha)G^{1/1-\sigma}}{\epsilon[\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}]} \quad , \tag{3.25}$$

and is directly proportional to the amount of labor in technology improvement sector. Notice that the first two terms in equation (3.25) are the decentralized technology growth rate (3.13). The rest of the expression is ambiguous in sign, and so (3.25) can not be ranked against the equilibrium solution. Some of the labor released from decentralized manufacturing will go into abatement, but some may also be allocated to non-polluting technology accumulation, in which case the first best technology growth is higher; $g_A^* > g_A^\circ$. Under other circumstances, however, pollution abatement incentives may draw labor out of *both* manufacturing and technological growth, leading to lower economic growth. Thus, neither labor in nor growth of technology can be ranked unambiguously against the decentralized solution.[8] In addition, the effect of pollution disutility on technology growth rates is ambiguous, since technology increases do not contribute to pollution, but require labor which could be used to abate pollution. Therefore, economic growth as well as current consumption may, but will not always, be sacrificed as a clean environment becomes more important.

In other endogenous growth models (Lucas, 1988; Bovenberg and Smulders, 1995), the socially optimal technology growth rate is unambiguously greater than the decentralized growth rate, since positive spillovers associated with technology will induce the social planner to allocate more resources to the growth sector. In this model with no positive externalities to motivate labor increases in the technology sector, additional labor allocations to the growth sector are motivated solely by incentives to reduce the negative environmental externality.

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[8] If emissions are caused by total output (polluting technology advances, as specified in footnote 3), the social planner will draw labor exclusively out of technology growth to abate pollution and will maintain the same labor in manufacturing as in the decentralized solution. Since technology accumulation is directly polluting in that case, the social planner is again moving labor from a polluting sector to a clean sector. However, because drawing labor out of technology advances will reduce the growth rate of the polluting process, whereas reducing manufacturing labor only reduces the level of emissions, abatement is more efficient via reductions in technology labor.

Growth rate of the pollution stock is given by

$$g_Z^* = \frac{\phi_1 \rho \alpha}{\delta + \epsilon \phi_1} - \frac{\delta}{\epsilon \sigma} K G^{1/1-\sigma} + \frac{\rho(1-\alpha)[\epsilon \sigma \phi_2 + \delta G^{1/1-\sigma}]}{\epsilon^2 \sigma \, [\phi_2 + \gamma(1-\sigma) G^{\sigma/1-\sigma}]} , \tag{3.26}$$

and may be optimally positive or negative.[9] This is a generalization from models (e.g., Tahvonen and Kuuluvainen, 1993; Bovenberg and Smulders, 1995) where an environmental stock is assumed to be constant over time. In this model, the pollution stock will be constant (declining) if

$$K G^{/1-\sigma} \frac{\delta}{\epsilon \sigma} = (>) \ \frac{\rho \alpha \phi_1}{\epsilon \phi_1 + \delta} + \frac{\rho(1-\alpha)[\epsilon \sigma \phi_2 + G^{1/1-\sigma}]}{\epsilon^2 \sigma [\phi_2 + \gamma(1-\sigma) G^{\sigma/1-\sigma}]} .$$

That is, if the social discount rate and emissions per unit resource in manufacturing are small, and the fixed capital stock is sufficiently large, the growth rate of pollution will possibly be zero or negative. When the disutility of pollution, ϵ, increases, both capital and labor move out of manufacturing and into abatement, slowing pollution stock growth rates further.

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[9] A negative growth rate implies that starting from an initial pollution stock level, the stock of pollution will asymptotically approach zero over time.

Notice that the total endowment of labor does not affect the growth rate of the pollution stock, a result similar to one found by Copeland and Taylor (1994). In both models, this results is driven by constant returns to labor in the growth sector, and is not due to the public nature of pollution.

Proposition 3:

The sustainable growth rate in the efficient solution is unambiguously larger than the decentralized sustainable growth rate.

Proof: see Appendix A.2.

The sustainable growth rate is given by

$$\begin{aligned} g_V{}^{*} = \delta L - \rho\alpha + \left(\frac{1-\sigma}{\sigma}\right)\delta K G^{1/1-\sigma} \\ - \frac{\rho(1-\alpha)[\epsilon\sigma\phi_2 + \delta(1-\sigma)G^{1/1-\sigma}]}{\epsilon\sigma[\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}]} \end{aligned} \tag{3.27}$$

and is unambiguously higher than the equilibrium rate (3.15) except in the (trivial) case where pollution does not affect utility (ϵ=0). As ϵ approaches zero, the social planner's optimal solutions collapse to the equilibrium solutions, as there are no other externalities in the economy. When pollution does affect utility, the social planner allocates resources to internalize the negative externality of emissions, and thereby increases the sustainable growth rate over the decentralized solution.

Unlike in the decentralized solution, the efficient instantaneous utility growth rate is increasing in both labor and capital endowments. As the labor endowment increases, all additional labor will go into the technology sector, increasing the economic growth component of sustainable utility. Increases in the capital endowment will also increase the rate of growth of instantaneous utility, since capital may be allocated for pollution abatement. In contrast, we saw that capital increases in the decentralized economy raised emissions and lowered the growth of instantaneous utility, since capital was never used for abatement. Increases in the social discount rate have an ambiguous effect on technology growth, but will lower the sustainable growth rate, as increases in pollution growth from increased ρ outweigh any potential positive increases in technology growth.

Increases in the productivity of either the abatement (γ) or the growth (δ) sectors will cause factors used in that sector to unambiguously increase. When γ rises, pollution growth slows as labor from the technology sector is re-allocated to abatement. Therefore, growth in technology is traded for improvements in environmental quality, and the overall effect on utility growth is ambiguous. When productivity of labor in technology, δ, is increased however, *manufacturing* labor is drawn into the technology sector, decreasing pollution growth while increasing technology and consumption growth. In the latter case, the sustainable growth rate will unambiguously increase.

3.5. Alternative Policy Objectives

Throughout Section 3.4, a benevolent social planner was assumed to have as a sole goal the maximization of social welfare. However, a government may wish, or be persuaded by lobby groups, to place additional restrictions on the economy. In this section, I explore what happens if the social planner's balanced growth path is constrained by policies which a) prohibit labor from being used for environmental maintenance, or b) restrict the economic growth rate to zero. Superscripts on solutions identify the relevant policy restriction under consideration. For both restrictions investigated, the social planner is assumed to maximize the intertemporal utility function (3.16) used in Section 3.4, subject to appropriate constraints. As with any restricted optimization, we know *a priori* that the second best maximum will be lower than the unrestricted solution.

3.5.1 Restricted Abatement

Suppose first that a politically influential industrial lobby opposes allocation of resources to environmental maintenance. Alternatively, with the idea of "catching-up" economically, a government may decide to defer consideration of environmental problems until after the country has gained in economic growth, and thus for the present puts no labor into pollution reduction.[10] Because of the Cobb-Douglas relationship between capital and labor in abatement, no capital will be allocated to abatement under this restriction. (A similar result obtains, of course, if the restriction is placed on abatement capital.) The restricted social planner's problem is to maximize intertemporal utility (3.16), with $L_Z=0$ and $K_Z=0$. The relevant constraints are therefore (3.17) and (3.18), along with

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[10] In an overlapping generations model, Tahvonen and Kuuluvainen (1993) show that when a country begins with a low level of physical capital, initial neglect of environmental maintenance may be an optimal strategy to prevent being trapped in a

$$\dot{z}(t) = [\phi_1 L_M + \phi_2 K_M] z(t) \tag{3.28}$$

and

$$L = L_M + L_A \qquad \textit{and} \qquad K = K_M \ . \tag{3.29}$$

No polluting emissions are abated (3.28), all labor is allocated to manufacturing and technology accumulation, and all capital is used in manufacturing (3.29). Note that these constraints are identical to those for the decentralized economy.

Proposition 4:

Even with a prohibition on abatement activity, the social planner's restricted second-best path will have lower pollution stock growth rates and higher sustainable growth than the decentralized solution.

Proof: See Appendix A.3.

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low-level no-growth equilibrium. While this is not in fact an optimal policy here, the idea may be politically attractive to less developed countries.

Just as in the decentralized solution, the restricted social planner has no labor or capital in emissions abatement and all increases in capital endowment are necessarily pollution increasing. However, the planner is able to internalize partially the pollution externality by allocating labor away from emissions-producing manufacturing and into non-polluting technology advances.

Labor in manufacturing,

$$L_M^a = \frac{\rho\alpha}{\delta} - \frac{\rho\alpha\epsilon\phi_1}{\delta(\delta + \epsilon\phi_1)} \quad , \tag{3.30}$$

is lower than in the decentralized solution (3.12), and is in fact the same as in the first best. Labor in, and thus the growth rate of, technology is higher than along the equilibrium path,

$$g_A^a = \delta L - \rho\alpha + \frac{\rho\alpha\epsilon\phi_1}{\delta + \epsilon\phi_1} \quad . \tag{3.31}$$

The first two terms of the growth rate are the decentralized growth rate, and the final term, which is positive, represents the effect of the pollution externality on the social planner's restricted best choices. The technology abatement sector will absorb all additions of labor in the economy.

Pollution growth is unambiguously lower than in the decentralized solution, even though there is no direct abatement activity,

$$g_Z^a = \frac{\phi_1\rho\alpha}{\delta} + \phi_2 K - \frac{\rho\alpha\epsilon\phi_1^2}{\delta(\delta + \epsilon\phi_1)} \quad . \tag{3.32}$$

The negative effect of pollution is partially mitigated (compare to (3.14)), as represented by the final term in (3.32), through decreasing labor in manufacturing. Pollution stock growth will, however, always be positive and greater than the unrestricted social optimum.

Technological advances, and thus consumption growth, are more rapid under this policy than along either the equilibrium or efficient paths. As before, this is not the result of attempts by the social planner to internalize technology spillovers; rather, the social planner has incentives to reduce the pollution stock and in this restricted case can only do it by reducing labor in manufacturing. All labor that optimally would have been used in abatement, as well as some additional manufacturing labor, will move to the growth sector and increase economic growth rates.

The combination of lower pollution and higher technology growth rates leads to a sustainable growth rate,

$$g_V^a = \delta L - \rho\alpha - \epsilon\phi_2 K \quad , \tag{3.33}$$

which is unambiguously larger than in the decentralized solution (3.15), although of course lower than the unrestricted first best (3.27).[11]

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[11] This result is partially robust to the pollution neutrality of technology growth. With polluting technology growth (specified in footnote 3), a policy restriction of $L_Z=0$ will again result in the first best labor allocation to manufacturing, and all abatement labor will again go into technology accumulation.

Recall, however, that in the model with polluting technology growth, the decentralized and first best manufacturing labor allocations are the same. Since both technology level and manufacturing labor contribute to pollution, the first best solution is not able to mitigate pollution by shifting labor from manufacturing to innovation, because both contribute to pollution. Thus, the decentralized labor in final goods is also the first best allocation, and equal also to the second best under this restriction.

3.5.2 Restricted Economic Growth

Some writers (see for example Meadows, 1992) believe that a moratorium on economic growth is the only way to maintain environmental quality over the long run. Such calls for no economic growth seem predicated on the assumption that any positive amount of economic growth will increase environmental degradation. To some extent, I believe (see also Daly, 1987) that such a view arises largely due to disagreements about what contributes to and is measured as economic growth. Since quality improvements and technology accumulation are an important part of growth (Grossman and Helpman, 1991; Thompson and Waldo, 1995), a significant proportion of economic growth is unlikely to increase pollution substantially. However, since zero growth ideas are popular in some policy and lobbying circles, I explore the impact of such a policy in this model.

With economic growth defined as technology accumulation, setting growth equal to zero entails restricting the labor allocation of the technology sector to zero, $L_A=0$. The social planner will maximize representative utility (3.16) subject to previous constraints (3.17) and (3.19), with labor used only in manufacturing and abatement,

$$L = L_M + L_Z \qquad \text{and} \qquad K = K_M + K_Z \quad . \tag{3.34}$$

Proposition 5:

When no economic growth is allowed, pollution growth rates may be higher than along either the social optimum or decentralized paths.

Proof: See Appendix A.4.

With this restriction, explicit solutions are not attainable. First order conditions from the usual optimality procedures can be reduced to two equations in L_Z and K_Z:

$$\rho = \frac{\epsilon\ (L - L_Z)}{\alpha}\ [\phi_1 + \gamma \sigma L_Z^{\sigma-1} K_Z^{1-\sigma}]\ , \tag{3.35}$$

which comes from the equalization of marginal product of labor in manufacturing and abatement (*LAL*); and

$$\rho = \frac{\epsilon\ (K - K_Z)}{(1-\alpha)}\ [\phi_2 + \gamma(1-\sigma) L_Z^{\sigma} K_Z^{-\sigma}]\ , \tag{3.36}$$

from equalization of marginal product of manufacturing and abatement capital (*KAL*).

The intersection of *LAL* and *KAL* is illustrated in Figure 3.2. Both lines can be shown to slope upward, with the slope of *LAL* greater than the slope of *KAL* for any given value of L_Z. This, along with the fact that only *LAL* has a positive intercept along the L_Z axis, implies that a (unique) intersection always exists. Necessary and sufficient conditions for an interior solution for L_Z and K_Z is that

$$L > \max \left\{ \frac{(1-\alpha)\rho}{\epsilon \phi_2}, \frac{\alpha \rho}{\epsilon \phi_1} \right\} .$$

Otherwise, no labor or capital will be allocated to abatement. (For proof, see Appendix A.4.)

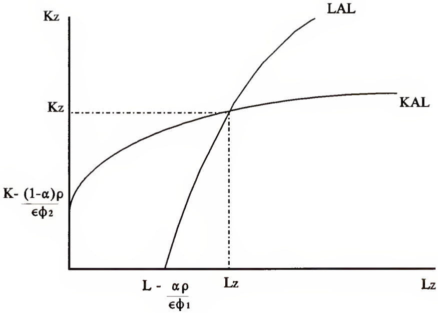

Figure 3.2 Equilibrium under Restricted Economic Growth

Abatement activity (growth rate of the pollution stock) will increase (decrease) as endowments of capital and labor increase, and as the disutility of pollution or technology for abatement increases. Increases in per unit emissions from either labor or capital will have an ambiguous effect. Increases in the marginal utility of consumption or the social discount rate will decrease allocations to the abatement sector, and therefore increase the pollution growth rate.

The implicit allocation of labor and capital to manufacturing and abatement (from Figure 3.2) can not be ranked against either the first best or decentralized solution. Consequently, the pollution growth rate can not be ranked against either growth rate.[12] This result implies the disturbing possibility that the growth of pollution stock may be higher than in the first best, or greater even than in the decentralized situation. Although presumably the goal of a zero economic growth policy is to forestall environmental degradation, these results show that the reverse can happen and pollution may grow more rapidly under such a policy. This environmentally unfriendly result may occur if strong incentives to increase consumption are felt when the growth rate of consumption is constrained to be zero. Since final goods output cannot be increased through technology growth, pressure for higher consumption levels may draw substantial amounts of capital and labor into manufacturing, increasing emissions and decreasing abatement activity, thus causing higher pollution growth. If there is positive growth in the pollution stock, the instantaneous utility growth rate will always be negative.[13]

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[12] With a simpler Ricardian technology ($\alpha=1$), the ambiguity of these results remains although explicit solutions are obtained.

3.6. Conclusions

The potential conflict between economic growth, consumption and environmental quality is at the center of the sustainable development debate. A limited amount of resources must be divided between economic growth and environmental maintenance. This paper investigates an economy where a) non-polluting technology accumulation leads to economic growth, b) resources devoted to final goods manufacturing are polluting, and c) resources may be allocated to pollution abatement. Distinguishing this research from other environment and growth papers is the fact that pollution is not directly linked to economic growth and thus economic and pollution growth rates need not have a one to one correspondence.

A decentralized economy will have faster pollution growth than the first-best balanced growth rate, but the rate of technology accumulation (economic growth) may be larger or smaller. A social planner may devote labor and capital to pollution reduction, and environmental quality may optimally improve or degrade over time. Government policies will not always have the desired effects. Social policy restrictions which prohibit labor in pollution abatement, perhaps an aim of a manufacturing lobby, will lead to manufacturing labor allocations that are below the equilibrium levels, and in fact the same as the efficient allocations. Pollution growth will be higher than in the first best solution, but lower than the equilibrium rate. A policy which restricts economic growth to zero, presumably in hopes of preventing environmental degradation, may actually increase the growth rate of pollution.

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[13] When polluting technology growth is specified (footnote 3), pollution growth has a one to one relationship with technology growth, and a prohibition on innovation will lead to a constant pollution stock. Utility growth will always be zero.

Because the specification of non-polluting technology advances is restrictive, results throughout are compared to a model where higher technology levels result in higher emissions levels. In this case, a direct link between technology and emissions leads to a one to one correspondence between economic and pollution growth rates. As a result, a policy of zero economic growth will lead to a constant pollution stock (the converse will also hold).

The sign and magnitude of the first best rate of pollution stock growth for this model depends crucially on parameters describing the disutility of pollution and the efficiency of pollution abatement. This may support the claims of less developed countries who argue that because they are more tolerant of polluted conditions (and have more pressing poverty problems or better natural assimilative capacities), they should be allowed to have a higher rate of pollution growth in international agreements. In addition, the results highlight the potential role for transfers in pollution abatement technology to reduce the growth rate of pollution in less developed countries. More advance pollution reduction techniques not only increase the efficiency of the labor already in abatement but will also draw additional labor into the pollution reduction sector.

This model shows that the path of positive sustained growth in social utility (a proxy for sustainable development) does not necessitate zero economic growth when growth is at least partially non-polluting. A positive level of steady-state growth can be achieved while environmental quality is maintained or improved, since optimal pollution stock growth may be zero, negative or positive. However, this paper takes an extreme position, modeling all economic growth as non-polluting, whereas many previous papers (with exceptions of Hung *et al.*, 1974; Bovenberg and Smulders, 1995) have taken the other extreme of exclusively pollution-increasing growth. Since the evolution of environmental degradation is of critical importance to the results of these models, and environmental problems are likely to have a wide variety of appropriate representations, generalizing from any one analysis must be avoided. Careful identification and specification of the relevant environmental/economic interaction is essential for developing appropriate policies to promote economic growth while maintaining environmental quality.

CHAPTER 4
GROWTH, TRADE AND THE ENVIRONMENT

4.1. Introduction

In the last few years environmental problems have become a central issue both for the public at large and among policy makers. Understanding the linkages among trade reform, economic growth policy and environmental degradation is crucial for determining what policies are appropriate and sufficient for optimal regulation of international environmental externalities. The nature of the interactions will vary with externality characteristics, and a cohesive look at international pollution spillovers, trade and growth is necessary for even preliminary policy prescriptions. I use a two-country model of endogenously increasing human capital where emissions from each country contribute to a global pollution externality that may take the form of either a stock or flow pollutant. I specifically look at the effect of trade and type of pollution, the effect of unilateral reductions in emissions, and the use of domestic and trade interventions in regulating a transboundary externality.[1]

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[1] There are, of course, international issues connected with environmental problems beyond those I consider here. For example, strict domestic environmental policies are sometimes feared to lead to reduced competitiveness with countries with lower standards, or to industrial flight to less developed countries. Although theoretical results are mixed (Nestor and Pasurka, 1993; Oates *et al.*, 1993; Markusen *et al.*, 1993; Copeland and

A problem of international externalities arises when emissions generated by one country spill over into another, or when polluting activity in all countries adds to a global pollution stock. An affected country is limited in its ability to intervene in the internal affairs of the polluting country. Previous research with transboundary spillovers of pollution (Maler, 1990; Hoel, 1991, 1994; Deardorff, 1995) has shown that nationally optimal policies will not be globally optimal, and thus free riding occurs.[2] Hoel (1991) has the environmentally distressing result that unilateral reductions in emissions by one country may actually lead to increased world emissions as other countries will increase emissions in response to unilateral abatement. In this paper, I consider pollution as both a flow variable (as in the above papers) and as a dynamic stock variable with international spillovers, and in part examine the effect of unilateral reductions in pollution emissions, where one country has the ability to abate pollution and the other does not.

Taylor, 1994a, 1994b), empirical studies have found little empirical evidence that domestic environmental regulations affect trade, or that significant amounts of industrial flight occur (Tobey, 1990; Grossman and Krueger, 1993). Environmentalists, on the other hand, maintain that concerns with competitiveness may lead to the imposition of weaker government regulations. Barrett (1994a) finds that incentives will exist for imposition of either too strong or too weak standards.

[2] There is a growing literature exploring the participation in and stability of international environmental agreements. If stable coalitions exist, they tend to involve only a fraction of the negotiating countries (Carraro and Siniscalco, 1993; Barrett, 1994b, 1994c; Hoel, 1994). Cooperating countries can increase the number of signatories through transfers (Carraro and Siniscalco, 1993; Hoel, 1994), or through the credible threat of trade restrictions (Barrett 1994d) or domestic subsidies (Richer and Stranlund, 1995).

Both domestic and international pollution externalities may be affected by economic growth or international trade. Some environmentalists believe that increased trade and growth will lead to more environmental degradation, while economists have argued that if the environment is a normal good, the demand for environmental quality will increase as incomes rise. Empirically, the relationship between income and pollution levels is dependent on the specific pollutant being examined (Grossman and Krueger, 1993; Shafik, 1994). Theoretical results with local pollution have indicated that environmental degradation may increase or decrease with growth or trade (Chichilnisky, 1993; Lopez, 1994; Copeland and Taylor, 1994a, 1994b). The effect of trade in the presence of international pollution spillovers is less well studied, although there is some evidence that international trade has little impact on environmental quality (Perroni and Wigle, 1994). I examine the effect of increased trade and growth using a simple human capital accumulation model. The use of an endogenous growth framework to model environmental externalities is a fairly recent addition to environmental literature (Ligthart and van der Ploeg, 1994; Jones and Manuelli, 1995; Mohtadi, 1996), and international spillovers of pollution and trade have yet to be incorporated. Thus, my model also contributes to the endogenous growth/environment literature by considering international spillovers between trading countries.

The model presented here is novel in the source of the environmental externality. Most growth/environment models (e.g. Barrett, 1992; Tahvonen and Kuuluvainen, 1993; John and Pecchenino, 1994; and previous citations), have polluting emissions increasing directly with final goods output, leading to a one to one correspondence between pollution and economic growth. However, an inflexible link between growth and environmental degradation seems neither necessary, nor always reasonable. It is not clear, for example, that the accumulation of human capital (as in Lucas, 1988) or improvements in product quality should lead to more pollution, and a recent study (Thompson and Waldo, 1995) shows that up to 75% of all economic growth is due to quality increases. In addition, if increases in technology allow for more efficient production processes, the use of raw materials and resources should not increase with output. Allowing for non-polluting growth provides greater flexibility in the model and more realism for some environmental externalities.

I consider environmental problems in a two country model where emissions from both countries affect all consumers, and human capital is accumulated in both countries. Increases in the level of human capital do not lead to higher pollution levels; rather, as in Chapter 3, emissions are generated in proportion to the labor in manufacturing and can be reduced by allocation of labor to a pollution abatement sector.[3] Trade-offs between growth and environmental degradation are taken into account by allowing labor to be allocated to activities that are pollution-increasing (manufacturing), pollution-decreasing (abatement), or pollution-neutral (accumulation of human capital). The countries produce different goods and the North is distinguished in that abatement technology is available, and the government may regulate emissions by imposing a tariff or a domestic tax.

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[3] In a closed economy model in Chapter 3, I use an endogenous growth framework where polluting emissions are linked to manufacturing labor and not to the total output, and find that the competitive equilibrium has higher pollution growth rates than the socially optimal solution. Optimal growth of the pollution stock may be positive or negative, and following a policy of zero economic growth may increase the rate of environmental degradation.

Some results obtained here are unique in the environmental literature. Although the South does not use labor in pollution abatement, the relative growth in human capital in the South may be higher or lower than in the North when the North is following optimal policies. Increases in trade that do not affect funding for abatement will unambiguously lead to increased abatement activity in the North; that is, gains from trade are used to improve environmental quality. For policy to achieve the first best labor allocations, two instruments must be employed as the environmental externality induces distortions in both growth and level variables in the economy.

The effect of unilateral abatement activity is dependent on whether the environmental externality takes the form of a stock or flow. With a flow pollutant, a free rider problem exists where the North will decrease abatement effort in response to lower Southern emissions, and therefore unilateral reductions may not decrease world pollution. For stock pollution however, optimal labor allocations in the North are not affected by the South's emissions levels, and countries do not increase emissions in response to other countries' abatement efforts. The intertemporal dimension to the stock pollution externality may attenuate the free rider problem to some extent.

The remainder of the paper is organized as follows. Section 4.2 describes the decentralized equilibria in the South and the North for a household producer-consumer problem with international spillovers of pollution and endogenously growing economies. Section 4.3 compares the two countries' solutions, and explores the effect of trade on abatement activity. Section 4.4 solves for the efficient (socially optimal) path in the presence of a pollution stock or a pollution flow externality, and section 4.5 determines policy interventions which lead to the first best labor allocations and growth rates in the North. Section 4.6 concludes.

4.2. The Model

I assume a two-country framework, where the countries are affected by the same global pollution externality. The Northern government may take an active role in pollution abatement, whereas the South does not possess any abatement technology. The North and South each produce a single differentiated final good, using human capital and labor as specific inputs. The North and South trade in the domestically produced goods and so both goods are consumed in each country. Labor may also be devoted to human capital accumulation. To focus solely on the effect of an environmental externality, I use a model for which, in the absence of pollution, the competitive equilibrium is optimal and displays endogenous growth (as in Barro, 1990; Rebelo, 1991).

A continuum of homogenous households exists in both the North and South, and each is simultaneously a producer and consumer (c.f., Barro, 1990; Mohtadi and Roe, 1992). Representative households maximize an intertemporal utility function

$$U = \int_0^\infty e^{-\rho t} \ln V(t)\, dt \quad , \tag{4.1}$$

where $\rho > 0$ is the constant subjective discount rate for both countries. *ln V(t)* is the instantaneous subutility function which depends on the levels of consumption and on the global pollution externality. Function *V(t)* is identical in the two countries and takes the form

$$V(t) = c_x(t)^{1-\eta}\, c_y(t)^{\eta}\, z(t)^{-\epsilon} \quad ,$$

where $c_x(t)$ and $c_y(t)$ are levels of consumption of two goods $x(t)$ and $y(t)$, and $z(t)$ is global pollution. Parameters η and ϵ are positive constants representing utility weights on consumption and pollution respectively. A Cobb-Douglas relationship between traded goods assures constant consumption shares of each good in both countries.

Households in the North and South combine the current level of human capital, $A(t)$, with manufacturing labor, L_M, to produce final goods $x(t)$ and $y(t)$ respectively, using linear production functions:

$$x(t) = A(t) L_M \tag{4.2}$$

$$y(t) = A^S(t) L_M^S \quad . \tag{4.3}$$

A superscripted s will be used to denote Southern parameters and variables. From preferences given above, the consumption goods are imperfect substitutes of each other. Producer-households can increase the marginal productivity of labor in manufacturing by increasing their levels of human capital:

$$\dot{A}(t) = A(t)\,\delta L_A \tag{4.4}$$

$$\dot{A}^S(t) = A^S(t)\,\delta^S L_A^S \quad . \tag{4.5}$$

L_A is the labor devoted to human capital increases and δ is a productivity parameter. There is no transfer or depreciation of human capital. The income from production for a representative household is $E(t)=q_x(t)x(t)$ in the North, and $E^S(t)=q_y(t)y(t)$ in the South, where $q_x(t)$ and $q_y(t)$ are international prices for the freely traded goods $x(t)$ and $y(t)$.[4]

Transboundary pollution is generated during the production of both consumption goods, and completely spill over from one country to the other. Emissions are proportional to the labor allocated to manufacturing: ϕL_M in the North, and $\phi^S L_M^S$ in the South, where ϕ and ϕ^S are measures of how dirty the manufacturing process is for a particular final good. Emissions do not increase with levels of human capital, and may be reduced in the North by pollution abatement effort. Net pollution emissions are $P^S(t)=\phi^S L_M^S$ (South) and $P(t)=\phi L_M - \gamma L_Z^\sigma$ (North), where L_Z is labor devoted to pollution abatement. There are non-increasing returns to labor in abatement, $\sigma \leq 1$, and γ is a positive constant. I assume that pollution abatement technology is only available in the North.

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[4] The existence of transportation costs reduces consumption of the foreign-produced good in both countries but does not alter results in any substantive way.

The environmental externality, *z(t)*, affects consumer utility and is considered alternatively as a flow and as a stock variable. As a flow, utility is affected by the sum of net emissions at any given point in time,

$$z(t) = P(t) + P^S(t) \quad . \tag{4.6}$$

Smoke and atmospheric heavy particles are examples of this type of pollutant. Increases in emissions by either country will raise the level of the global pollution externality by that amount. With this specification, pollution does not have intertemporal spillovers.

On the other hand, many pollution externalities take the form of growing stocks, for example atmospheric carbon dioxide or heavy metal accumulation in lakes. Thus, I also consider the case where pollution contributes to a global stock. Incorporation of emissions into the pollution stock is assumed to be dependent on the current stock level,

$$\dot{z}(t) = [P(t) + P^S(t)]z(t) \quad . \tag{4.7}$$

When the stock is low, additional pollution does not increase the environmental externality by as much as when the stock is high; with a large *z(t)*, any additional pollution will have a greater effect on consumer utility. This specification captures the idea that the natural assimilative capacity of the environment decreases with higher pollution levels. Equation (4.7) allows for a steady state balanced growth path with constant pollution growth which may be positive, negative or zero.

When the emissions flow specification is used, only choices made in a given period affect the pollution disutility experienced in that period. With the case of stock pollution, however, choices in each period will affect all future periods as well; even if emissions are zero in a period, a positive (and in that case constant) pollution stock will still create disutility. In both cases it is important note that this model does not exclude the possibility of a steady state equilibrium with zero polluting emissions or zero pollution growth.

Households in both countries supply labor inelastically to home production and human capital accumulation, and in the North to the government sector. For each household the labor constraint is assumed to hold: $L=L_M+L_A+L_Z$ in the North, and $L^S=L_M{}^S+L_A{}^S$ in the South. Labor is immobile across countries, and total population is the same in the two countries.

4.2.1 Decentralized Equilibrium in the South

The South has a decentralized economy, and does not possess abatement technology. Households maximize intertemporal utility (4.1) subject to the constraints on labor supply, production (4.3), evolution of human capital (4.5), and a budget constraint. The budget constraint of the representative household is

$$E^S(t) = q_y(t)y(t) = c_x(t)q_x(t) + c_y(t)q_y(t) \quad .$$

All income is from production of good *y(t)*, and households spend all income on consumption of the two goods.

Households choose consumption levels for the two goods as well as allocations of labor between manufacturing and human capital accumulation. The level of the environmental externality is of course taken as given. Standard dynamic optimization procedures for a current value Hamiltonian problem give first order conditions that yield

$$\frac{c_x^S}{c_y^S} = \frac{(1-\eta)\ q_y}{\eta\ q_x} \quad .$$

Then, using the budget constraint, consumption expenditures as a function of income are

$$q_y\ c_y^S = \eta E^S \tag{4.8}$$

$$q_x c_x^S = (1-\eta)E^S \quad , \tag{4.9}$$

which are similar to static solutions. Consumption of both goods will increase as the household income, E^S, increases. Presence of a transport cost can be shown to decrease consumption of the imported good. From the production function for output, income and thus consumption of both goods will increase over time if human capital accumulation takes place, which will occur if labor is devoted to its accumulation, i.e., if $L_A > 0$.

Labor allocations to manufacturing and human capital will be constant along a steady state growth path, and can be solved for using the first order conditions from the dynamic maximization problem equating marginal products of labor, and the constraint for human capital evolution:

$$L_M^S = \frac{\rho}{\delta^S} \qquad and \tag{4.10}$$

$$L_A^S = L^S - \frac{\rho}{\delta^S} \qquad . \tag{4.11}$$

No pollution abatement is undertaken, as no abatement technology is available to the government. The labor in manufacturing will increase as the discount rate increases - when the current period is more highly valued, labor devoted to growth will decrease. As the labor endowment of a representative household increases, all additional labor is put into human capital increases.[5] Recall that since there are no spillovers in human capital accumulation, these equilibrium labor allocations would also be efficient in the absence of a pollution externality. Note that if the discount rate is high and labor endowment low, there may be no human capital accumulation, and in that case, no growth takes place and all labor is devoted to manufacturing.

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[5] This result comes from the specification of constant returns to scale in human capital accumulation.

4.2.2 Decentralized Equilibrium in the North

Unlike in the South, the Northern government may take an active role in reducing pollution by hiring labor to abate emissions. I assume two policy instruments are available to the government for raising abatement revenue: taxes on households' manufacturing labor, t_M, and a tariff on the imported good, t_T. The government budget constraint in the North is

$$B(t) = t_M L_M + t_T q_y(t) c_y(t) = w L_Z \quad ,$$

where $t_T q_y c_y$ is tariff revenue, L_Z is the labor hired to abate emissions, and w is the wage paid to abatement labor.

Taking the pollution externality as given, households in the North will maximize intertemporal utility (4.1) subject to the production technology (4.2), the constraint on the evolution of human capital (4.4), and a budget constraint given by

$$\begin{aligned} E(t) &= q_x(t) x(t) + w L_z \\ &= q_x(t) c_x(t) + q_y(t) c_y(t)(1 + t_T) + t_M L_M \end{aligned} .$$

Household income is the sum of wages for pollution abatement labor and the value of household production output. All income is used to purchase the two consumption goods,[6] and to pay the labor tax. As in the South, if human capital accumulation occurs, $x(t)$ and thus household income grow over time. The utility optimization of a representative household will involve choosing consumption and labor allocations taking government taxes, tariffs, and the environmental externality as given.

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[6] Because the South has a monopoly on trade in $y(t)$, the whole price of the tariff will be passed on to consumers in the North.

Again defining the steady state by constant labor allocations, first order conditions from a standard current value Hamiltonian problem can be solved using the household or government budget constraints for the Northern labor allocations as functions of the tariff revenue, manufacturing tax, and government wage rate:

$$L_M = \frac{\rho w}{\delta(w + t_M)} \tag{4.12}$$

$$L_A = \frac{wL - t_T q_y c_y}{w} - \frac{\rho}{\delta} \tag{4.13}$$

and

$$L_Z = \frac{t_T q_y c_y}{w} + \frac{\rho t_M}{\delta(w + t_M)} \quad . \tag{4.14}$$

I defer discuss of these results until the next section.

Next, first order conditions from the household maximization problem give the consumption ratio

$$\frac{c_x}{c_y} = \left[\frac{1-\eta}{\eta}\right](1 + t_T)\frac{q_y}{q_x} \quad .$$

And, using the household budget constraint, the consumption choices are given by, Barriers to trade in the form of tariffs (and similarly for transport costs if present) will decrease the volume of trade, and more of the domestic good will be consumed.

$$q_x c_x = \frac{(1-\eta)\rho w\,(1 + t_T)}{\delta[1 + t_T(1 - \eta)]} \tag{4.15}$$

$$q_y c_y = \frac{\eta \rho w}{\delta[1 + t_T(1 - \eta)]} \quad . \tag{4.16}$$

Because taxes and tariffs affect the level of manufacturing and the economic growth rate, the consumption expenditures on each good are no longer a simple function of the relative utility weight of that good, as was seen for the South.

To solve for a world trade equilibrium, note that the assumption of equal labor endowments in the North and South simplifies the balanced trade condition to that for a representative household, $q_x c_x^S = q_y c_y$.

4.3. Equilibrium Results

The first point of interest in the equilibrium solutions is to compare the decentralized solutions for the countries with and without abatement technology and regulation. From (4.2) and (4.3), production grows at the same rate as human capital, and I refer to both as the economic growth rates.

Proposition 1

For any positive tariff ($t_T > 0$), the economic growth rate of the South exceeds the growth rate in the North. In addition, the growth rate in the North monotonically declines in the tariff since as the tariff increases, labor is taken out of human capital accumulation and put into abatement.

Proof: Setting the Northern wage in abatement as the numeraire, and using (4.16) in (4.12)-(4.14), we obtain Northern labor allocations:

$$L_M = \frac{\rho}{\delta(1 + t_M)} \tag{4.17}$$

$$L_A = L - \frac{\rho\,(1 + t_T)}{\delta\,[1 + t_T(1-\eta)]} \tag{4.18}$$

and

$$L_Z = \frac{t_T \eta \rho}{\delta\,[1 + t_T(1-\eta)]} + \frac{\rho\, t_M}{\delta(1 + t_M)} \tag{4.19}$$

The economy grows in each country at the same rate as human capital is accumulated. Thus, substituting labor in human capital accumulation into the constraint on evolution of human capital gives the economic growth rates:

$$g^S = \delta L - \rho \qquad \textit{and} \qquad g^N = \delta L - \frac{\rho(1 + t_T)}{1 + t_T(1-\eta)} \;.$$

Comparison of these, and of above labor allocations with those in the South, (4.10) and (4.11), establishes the proposition.

The tax and tariff will affect the labor allocations in the North, as well as the Northern economic growth rate. By assumption, only the North will put labor into abatement, and will only do so with a positive tax and/or tariff. The tariff does not affect labor in manufacturing, but decreases labor in human capital accumulation by shifting it to abatement. Increasing the tariff increases abatement labor because human capital labor is lower, but also acts to reduced the economic growth rate.[7] This is similar to the result in Ligthart and van der Ploeg (1994) that taxes will slow economic growth. The same result, however, does not hold true for a manufacturing tax, which decreases labor in that sector, and moves all freed labor into pollution abatement. This does not affect the economic growth rate, but will unambiguously reduce pollution, as fewer emissions are produced and more are abated.

The result that tariff increases lead to less environmental degradation albeit slower growth is interesting, but it is not apparent from this analysis if the environmental gains are due to increased revenue from the tariff, or if, as some environmentalists argue, trade itself leads to higher environmental degradation and therefore if discouraged through a tariff, environmental quality will increase. A decomposition of this result into the effect of abatement revenue and the effect of trade is discussed in Proposition 2.

Proposition 2

Increases in the tariff will increase revenue for abatement, which consequently improves environmental quality. However, holding abatement revenue

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[7] Unlike these two interventions, a tax on human capital accumulation labor may have an ambiguous effect on the pollution growth rates. A tax on human capital accumulation decreases labor in this sector, increases labor in manufacturing, and has an ambiguous effect on L_Z. When this tax is high, the pollution problem is likely to increase, as both polluting manufacturing is increased and emissions-abating labor is reduced.

constant, increases in trade via decreasing the tariff will increase abatement effort and environmental quality.

Proof: For this proof, we reassign the numeraire to be the income of Southern households, $E^S(t)=1$. Then, from (4.9), $q_x c_x^S = 1-\eta$. Using this and (4.16) in the balanced trade condition, the Northern wage in terms of Southern income is given as

$$w = \frac{(1-\eta)\delta\ [1+t_T(1-\eta)]}{\eta\rho} \quad .$$

Substituting the wage rate into (4.16), the value of the goods imported to the North is given by

$$q_y c_y = (1-\eta) \ ,$$

which does not change as the tariff increases, a result driven by the Cobb-Douglas structure of preferences. Consequently, tariff revenue will increase as the tariff increases. Since labor in abatement increases as tariff revenue increases, from (4.14), the revenue effect of increasing tariffs will be to increase environmental quality.

Substituting the wage rate into (4.14), and holding tariff revenue (*TR*) constant, gives an expression for labor in abatement as a function of the tariff revenue and tariff rate separately,

$$L_Z = \frac{\eta\rho(TR)}{(1-\eta)\delta[1+t_T(1-\eta)]} + \frac{t_M\eta\rho^2}{(1-\eta)\delta^2[1+t_T(1-\eta)] - \eta\rho\delta t_M} \quad .$$

This expression for abatement effort is decreasing in the tariff, and establishes the last part of the proposition.

Holding tariff revenue constant, decreased trade will decrease abatement effort, and conversely, increased trade will increase abatement and environmental quality. This result implies that gains from trade are used to improve environmental quality. Intuitively, note that as the tariff falls more labor is allocated to human capital accumulation, which increases the growth rate of consumption. This leads to incentives to increase environmental quality, and thus additional labor is used in abatement. As mentioned above, however, the *overall* effect of a higher tariff is increased pollution abatement, as the revenue effect outweighs the gains from trade effect. The present of these conflicting forces, however, supports the view that trade policy is not the best instrument for providing pollution abatement funding.

Finally, the effects of the tariff and tax on balanced trade equilibrium consumption shares are summarized in Proposition 3.

Proposition 3

> *Manufacturing taxes do not change consumption shares, while the net effect of a tariff is to decrease consumption of the Northern produced good in the South and increase it in the North.*

Proof: The market clearing conditions for the two goods are $x=c_x+c_x^S$, and $y=c_y+c_y^S$. Using these conditions and the ratios of consumption solved for earlier, we obtain

$$c_x = \frac{(1-\eta)(1+t_T)\,x}{1 + (1-\eta)t_T} \qquad \textit{and} \qquad c_y = (1-\eta)y \ ,$$

and

$$c_x^S = \frac{\eta x}{1+(1-\eta)(t_T)} \qquad \textit{and} \qquad c_y^S = \eta y \quad .$$

Comparative static analysis for t_T and t_M in these equations establishes the proposition.

The tariff on y does not affect the consumption shares for this good, as the whole cost of the tariff is passed on to consumers in the North and increases their consumption of the domestically produced good x. As the North consumes more x, the share of that good in the South will fall. These results are not dependent on, nor do they affect, the environmental externality motivation of the tariff.

4.4. Socially Optimal Labor Allocations

It is of interest to determine if trade and domestic policy interventions in the North can be used to obtain the first best growth rates. To do this, I solve for the nationally optimal labor allocations in the North, both for the case of stock pollution and for a flow pollution externality, and then use these solutions in section 4.5 to determine what policy instruments can improve on the unregulated situation and possibly lead to the first best.

Assume that a Northern social planner takes into account the effect of labor in manufacturing on emissions, and taking Southern labor allocations, emissions, $e^S = \phi^S \rho / \delta^S$, and production, $y(t) = A^S(t)\rho/\delta^S$, as given. The North's consumption shares for each good will be proportional to the relative utility of the northern-produced good $(1-\eta)$.[8] The social planner's problem is therefore to maximize discounted utility

$$U = \int_0^\infty \left[(1-\eta)\ln c_x(t) + \eta \ln c_y(t) - \epsilon \ln z(t)\right] e^{-\rho t} dt, \tag{4.20}$$

subject to (4.4), the full employment constraint in the North,

$$c_x(t) = (1-\eta)A(t)L_M \qquad and \qquad c_y(t) = (1-\eta)\frac{A^S(t)\rho}{\delta^S} \quad ,$$

and an equation governing emissions.

4.4.1 The Case of Stock Pollution

If emissions add to a global stock of pollution, there are two dynamic stocks (human capital and pollution) which the social planner must consider, and evolution of the pollution stock takes the form,

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[8] The consumption shares will be the same as in the decentralized solution, since the social planner will not introduce distortions into the prices faced by consumers in either country.

$$\dot{z}(t) = \left[\phi L_M + \frac{\phi^S \rho}{\delta^S} - \gamma L_Z^\sigma \right] z(t) \quad .$$

The socially optimal solution to this problem has properties described in Proposition 4.

Proposition 4

> *With stock pollution, a positive amount of abatement is always done, and the optimal rate of economic growth in the North may be greater or less than under a unregulated solution.*[9]

Proof: Standard dynamic optimization procedures determine the optimal allocations of labor and the corresponding growth rates. First order conditions equate the marginal product of labor in all three sectors, and nationally optimal allocations of labor are

$$L_M^* = \frac{\rho(1-\eta)}{\epsilon\phi + \delta(1-\eta)} \tag{4.21}$$

$$L_Z^* = \left[\frac{\epsilon\sigma\gamma}{\delta(1-\eta)} \right]^{\frac{1}{1-\sigma}} \tag{4.22}$$

and

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[9] Another interesting result, which is related to proposition 6, is that the first best labor allocations in this economy are exactly the same as those found in Chapter 3 for a closed economy not subject to international spillovers of pollution.

$$L_A^* = L - \frac{\rho(1-\eta)}{\epsilon\phi + \delta(1-\eta)} - \left[\frac{\epsilon\sigma\gamma}{\delta(1-\eta)}\right]^{\frac{1}{1-\sigma}} . \tag{4.23}$$

The proposition is established by comparing these optimal allocations to the decentralized no-abatement solutions [set tax and tariff levels to zero in (4.17)-(4.19)], or by comparing to the Southern allocations.

The socially optimal level of manufacturing labor is lower than in the unregulated economy, and since only the manufacturing tax affects this labor, $t_M > 0$ is necessary to approach the social optimum. The labor in technology can not be ranked between the social optimum and the decentralized solutions. Although the first best always has a positive amount of labor for pollution abatement, manufacturing labor maybe reduced by more than the amount given to abatement, resulting in higher levels of labor in human capital accumulation. It is important to note that this result is not a consequence of the social planner internalizing a technology or taking advantage of learning spillovers; recall that the competitive solution is optimal in the absence of an environmental externality. Rather, because labor in human capital growth is neutral with respect to emissions, internalization of the externality does not have a unidirectional effect on economic growth.

The optimal labor in abatement of stock pollution is always positive, and the resultant rate of pollution stock growth may be negative. If disutility of pollution is large, and sufficient labor is put into abatement and taken out of manufacturing, net emissions in the North, and possibly global stock growth, may be negative.

4.4.2 The Case of Flow Pollution

The social planner's solution when the environmental externality is a flow variable will again maximize the North's individual utility (4.20), with the same constraints on the total labor endowment and production functions. However, the pollution variable, *z(t)*, will depend only on instantaneous net emissions; that is, the externality will be specified by (4.6). In this case, the following is true.

Proposition 5

With flow pollution, emissions abatement activity is not always undertaken in the first best solution, and the economy growth rate may be greater or less than in the decentralized solution.

Proof: Again taking net Southern emissions as given, and setting equal to K, the socially optimal labor allocations can be calculated for flow emissions using the same method as above;

$$L_M^{**} = \frac{\rho\gamma}{\delta(\phi+\gamma)} \tag{4.24}$$

$$L_A^{**} = L - \frac{K}{\gamma} - \frac{\rho(1-\eta-\epsilon)}{\delta(1-\eta)} \tag{4.25}$$

and

$$L_Z^{**} = \frac{K}{\gamma} - \frac{\rho[\epsilon\gamma - \phi(1-\eta-\epsilon)]}{\delta(1-\eta)(\phi+\gamma)} \quad . \tag{4.26}$$

For some parameter values, labor in abatement (4.26) is not positive, and no abatement activity is undertaken. L_A^{**} cannot be ranked against $L_A=\delta L\text{-}\rho$, establishing the proposition.

Since labor allocations are constant along a balanced growth path, net emissions and therefore environmental degradation do not grow over time, unlike in the case of stock pollution. Although the stock externality specification always had a positive amount of labor allocated to pollution abatement, if Southern emissions K or the "dirtiness" of Northern manufacturing ϕ are not too great, it will be optimal to put no labor into abatement of flow pollution. Additionally, if abatement technology is poor, γ low, abatement activity may not be worthwhile. Because there is no accumulating stock of pollution, emissions may optimally not be reduced.

The flow pollution labor allocations differ in at least one striking way from stock pollution optimal solutions; that is in the effect of the disutility of pollution, ϵ. For stock pollution, increased ϵ leads to decreases in the polluting manufacturing labor. However, with flow pollution, the disutility parameter does not affect labor in manufacturing, but rather, increases in ϵ will decrease labor in abatement and move labor into human capital accumulation. This counter-intuitive result can be explained by noting that with flow pollution, consumption of the two goods can grow over time, although a pollution stock can not. Thus, increases in pollution disutility are compensated for by increasing the rate of human capital accumulation and thus of consumption.

Finally, the effect of pollution type on abatement effort is discussed in Proposition 6.

Proposition 6

Emissions from the South only affect Northern labor allocations and abatement effort in the case of flow pollution. With stock pollution, there is no free rider affect.

Proof: Compare equations (4.26) and (4.22).

With stock pollution, emissions from other countries do not enter into the optimal solution for labor allocations, and thus levels of abatement are not affected by foreign emissions. This result implies that, unlike in Hoel (1991), unilateral increases in abatement effort will not lead to decreased abatement by other countries. However, when consumer utility is only affected by instantaneous pollution flow, Southern pollution does affect the North's labor allocations. As Southern emissions increase, optimal abatement labor in the North increases and human capital accumulation decreases. Thus, the North will compensate for southern emissions, even though this will decrease the North's economic growth rate. Conversely, if net emissions from the South decrease, the North will decrease abatement, and thus unilateral abatement efforts may not decrease world pollution, as in Hoel (1991). Since stock and flow pollution have such different results, we must recognize that the effects of unilateral abatement efforts will depend on the nature of the environmental externality.

4.5. Optimal Trade and Production Taxes

There are two policy instruments available to the Northern government to affect polluting activities and to raise revenue for pollution abatement. In the previous sections we have seen that the environmental externality causes decentralized labor allocations in all sections to be distorted from the first best, and that the difference, and the direction of the difference, is dependent on the type of pollution. Although emissions are caused exclusively by labor in one section, inspection of the tax dependent labor allocations (4.17)-(4.19) shows that use of a single policy instrument is not sufficient to achieve the first best allocations in all sectors because the externality has both growth and level effects. Manufacturing labor is only affected by a tax in that labor, and human capital accumulation is only affected by a tariff, leading to Proposition 7.

Proposition 7

For either flow or stock pollution, a combination of a tariff (import subsidy) and manufacturing tax can achieve the first best labor allocations and growth rates.

Proof: Proposition 7 is obtained by directly equating the first best allocations with their policy dependent equivalents, (4.17) - (4.19), and solving for the intervention levels which give the first best labor allocations.

Because labor endowments are fixed, the three labor allocation equations are not independent and only two policies are necessary for reaching the first best solution in all sectors.

What are these optimal policies? For stock pollution, the combination of a positive tax on manufacturing $t_M = (\epsilon\phi)/[\delta(1-\eta)]$, and a tariff

$$t_T = \frac{G\delta[\delta(1-\eta) + \epsilon\phi] - \rho\epsilon\phi}{[\rho - \delta G(1-\eta)][\delta(1-\eta) + \epsilon\phi] - \delta\rho(1-\eta)^2}$$

where

$$G = \left[\frac{\epsilon\sigma\gamma}{\delta(1-\eta)}\right]^{\frac{1}{1-\sigma}} ,$$

will lead to optimal labor allocations and growth rates. The tariff does not affect labor in manufacturing, and acts only to adjust technology and abatement labor to the first best. Consequently, whenever a tariff is used in combination with a tax, the tax will be used to adjust labor in manufacturing and the tariff will balance pollution abatement and economic growth.

As the disutility of pollution increases, the optimal manufacturing tax will also increase, similar to results found by Ligthart and van der Ploeg (1994). However, increases in environmental concern, ϵ, will decrease the optimal tariff. This result may be due to the conflicting environmental effects of changing a tariff which were discussed in Proposition 2.

For the case of flow pollution, a combination of $t_M = \phi/\gamma$, and

$$t_T = \frac{K\delta(1-\eta) - \epsilon\rho\gamma}{(1-\eta)[\rho\gamma(\eta+\epsilon) - K\delta(1-\eta)]}$$

will lead to the first best labor allocations in all three sectors.

Here, the tax on manufacturing labor balances only how dirty manufacturing is against the efficiency of the abatement technology. Since ϵ does not affect manufacturing labor, disutility of pollution likewise does not affect the manufacturing labor tax. The tariff is increasing in Southern emissions, as increasing the tariff raises abatement activity, and more abatement is desirable as K increases. Note, however, that an increased tariff will not affect manufacturing choices (or emissions) in the South.

4.6. Conclusions

Many environmental externalities are characterized by geographical and/or intertemporal spillovers. Thus, appropriate analysis for pollution problems must incorporate global spillovers and consider both flow and stock types of externalities. In addition, because static results often differ from those found in dynamic economy models, incorporation of economic growth is appropriate and may be necessary for reasonable policy prescription results. In this paper, pollution emissions are generated by production in endogenously growing economies, and emissions from all countries add to an international pollution problem which causes disutility for consumers in all countries. Using this model, I examine the effect of transboundary pollution in a North-South framework, where the Northern government has access to pollution abatement technology and can fund abatement activity with a labor tax and a tariff.

I examine two types of externalities: one where instantaneous emissions affect consumer utility, and the other where utility is affected by a cumulative stock of pollution. Some of the main findings of this research are summarized below.

1) Along a market equilibrium path without government intervention, no labor will be used to abate pollution. When stock pollution exists, a positive amount of abatement will always be optimal and the stock may optimally increase or decrease over time. With flow pollution, abatement activity may or may not be optimally undertaken in the first best solution.

2) With a stock environmental externality, optimal labor allocations do not depend on the emissions or labor allocations of the other country, but optimal abatement with flow pollution will decrease as the level of net emissions from the other country decreases. Thus, results for flow but not stock pollution coincide with Hoel's (1991) finding that unilateral reductions in emissions may in fact lead to increased world pollution.
3) Holding fixed the tariff revenue used to fund abatement, increasing trade by decreasing tariffs or transport costs will lead to increases in abatement effort. Thus, gains from increased trade will be used to improve environmental quality.
4) Even though polluting emissions are generated solely by labor in manufacturing, a single tax on manufacturing labor will not achieve the socially optimal solutions, as emissions induce distortions in both level and growth components in the economy. However, implementation of a positive manufacturing tax and a tariff (or import subsidy) on the imported good is sufficient to obtain the first best labor allocations and growth rates for either type of pollution.

Clearly, many results in this model vary according to the specification of pollution type, and in addition may not be robust to the source of polluting emissions and the endogenous growth of the economy. Because the sources and characteristics of the environmental externalities facing society are diverse, it is important to use appropriate model specifications for development of policy guidelines. Consequently, pollution regulations should be largely externality specific, and a search for generally applicable prescriptions may often be in vain.

APPENDIX
PROOFS OF PROPOSITIONS IN CHAPTER 3

A.1. Equilibrium Solution

The decentralized solution is found by maximization of (3.7) subject to (3.8), (3.9) and (3.10). Assuming that all individuals are identical, I solve for society aggregates which will be easier to compare to the social planner's solutions. Summing over all identical individuals and dropping the time arguments, the aggregate current value Hamiltonian is

$$H = \ln(A L_M^{\alpha} K^{1-\alpha}) - \epsilon \ln \bar{z} + \mu [A\delta(L - L_M]$$

subject to

$$L_A = L - L_M \qquad \textit{and} \qquad \dot{A} = A \delta L_A$$

with control variable L_M, state variable A, and costate variable μ (the shadow price of technology). The first order conditions are

$$H_{L_M} = \frac{\alpha}{L_M} - \mu A \delta = 0 \quad , \qquad \text{(A.1.1)}$$

$$\frac{\dot{\mu}}{\mu} = \rho - \frac{1}{\mu A} - \delta(L - L_M) \quad , \qquad \text{(A.1.2)}$$

and constraints.

Along the balanced growth path, the growth rates of both A and μ are constant. Taking logarithms and differentiating (A.1.1) with respect to time, we obtain $\dot{A}/A = -\dot{\mu}/\mu$. That is, technology growth is equal to the negative of its shadow price growth. Thus, using the first order conditions and constraints, we can solve for (3.12) and the labor in technology.

Using labor in technology and the expression for the evolution of technology (3.9), we obtain (3.13); and from (3.12) and (3.11) we obtain the growth in the pollution stock (3.14). From (3.13) and (3.14), we see that we do not have either g_Z as a function or g_A, or vice versa. To demonstrate this, set $\phi_1=\phi_2=L=K=1$, and $\delta=.8$, $\alpha=.7$, and $\rho=.04$; which gives g_A=0.772 and $g_Z=1.035$. Now, setting $\delta=.9$, $\alpha=.7$ and $\rho=.1829$, we obtain g_A=0.772 again, but $g_Z=1.14$. A similar exercise will show that g_A is not a function of g_Z.

Finally, the sustainable growth rate (3.15) for the decentralized society is found using the growth rates (3.13) and (3.14) in (3.6).

A.2. Efficient Solution

The socially optimal solution is found by maximizing (3.16) subject to (3.17) - (3.20). Let μ(t) denote the shadow price of human capital, τ(t) be the shadow price of pollution and λ_L(t), λ_K(t) be the full employment constraint multipliers. Dropping time arguments, the current value Hamiltonian is given by

The first order conditions for this problem consist of (3.18) - (3.20) along with

$$H = \ln(AL_M^{\alpha}K_M^{1-\alpha}) - \epsilon \ln z + \mu[A\delta L_A] + \tau[\phi_1 L_M + \phi_2 K_M - \gamma L_Z^{\sigma} K_Z^{1-\sigma}]z + \lambda_L[L - L_M - L_A - L_Z] + \lambda_K[K - K_M - K_Z]$$

$$H_{L_M} = \frac{\alpha}{L_M} + \tau\phi_1 z - \lambda_L = 0$$

$$H_{L_A} = \mu AL\delta - \lambda_L = 0$$

$$H_{L_z} = -\tau\gamma\sigma L_Z^{\sigma-1} K_Z^{1-\sigma} z - \lambda_L = 0$$

$$H_{K_M} = \frac{(1-\alpha)}{K_M} + \tau\phi_2 z - \lambda_K = 0$$

$$H_{K_Z} = -\tau\gamma(1-\sigma) L_Z^{\sigma} K_Z^{-\sigma} z - \lambda_K = 0$$

and

$$\frac{\dot{\mu}}{\mu} = \rho - \frac{1}{\mu A} - \delta L_A \qquad \text{(A.2.1)}$$

$$\frac{\dot{\tau}}{\tau} = \rho + \frac{\epsilon}{\tau z} - \phi_1 L_M - \phi_2 K_M + \gamma L_Z^{\sigma} K^{1-\sigma} \qquad \text{(A.2.2)}$$

The rates of growth of technology, consumption and pollution (and thus their shadow prices) are constant along the balanced growth path. Taking logarithms and differentiating (A.2.1) and (A.2.2) with respect to time, recalling that labor and capital allocations are constant in the steady state, we find that on the balanced growth path:

$$\frac{\dot{A}}{A} + \frac{\dot{\mu}}{\mu} = 0 \qquad \textit{and} \qquad -\frac{\dot{\tau}}{\tau} - \frac{\dot{z}}{z} = 0 \quad .$$

The growth rates of technology and pollution are equal to the decline in their respective shadow prices.

From here, we use the first order conditions and constraints to solve for the resource allocations, (3.21) - (3.24). Using (3.18) and (3.20) with (3.21) and (3.23), we solve for the rate of growth in technology (3.25), which must be non-negative.

Then, using (3.19) with (3.21) - (3.24), we can solve for the rate of growth of pollution along the balanced growth path (3,26), which is not restricted in sign.

Lastly, to find the sustainable growth rate, use (3.25) and (3.26) in (3.6) to obtain (3.27).

We can show that the efficient allocations collapse to the equilibrium solutions where there is no disutility associated with pollution. From (3.21), letting $\epsilon=0$ yields $L_M^*=\alpha\rho/\delta$. Using L'Hôpital's rule in (3.27), we find that $\lim_{\epsilon\to 0} L_Z = 0$. From (3.22) and (3.24), we see that K_M increases and K_Z decreases as ϵ gets smaller. Capital will only be allocated to abatement if

$$\epsilon K > \frac{\rho(1-\alpha)}{\phi_2 + \gamma(1-\sigma)G^{\sigma/1-\sigma}} \quad .$$

Thus, as ϵ decreases, eventually $K_Z=0$ and all capital will be devoted to manufacturing, which is the decentralized allocation.

A.3. Restricted Abatement

Since abatement is a Cobb-Douglas function of labor and capital, when there is no labor in abatement, all abatement capital is unproductive, and thus $K_Z=0$ as well. The analysis of this policy is entirely analogous to that of the first-best social planner's problem, with the additional constraint of $L_Z=0$. Solutions for labor allocations and growth rates follow the procedure outlined in section A.2, with the current value Hamiltonian,

$$H = \ln(AL_M^{\alpha}K_M^{1-\alpha}) - \epsilon \ln z + \mu A\delta(L-L_M) + \tau[\phi_1 L_M + \phi_2 K_M]z$$

being maximized subject to (3.18), (3.28) and (3.29).

A.4. Restricted Economic Growth

When no economic growth is allowed, we must have $L_A=0$. The restricted social planner will maximize utility (3.16) with respect to (3.17), (3.19), $L=L_Z+L_M$, and $K=K_Z+K_M$. The relevant Hamiltonian is

$$H = \ln(A L_M^{\alpha} K_M^{1-\alpha}) - \epsilon \ln z + \tau[\phi_1 L_M + \phi_2 K_M - \gamma L_Z^{\sigma} K_Z^{1-\sigma}] \\ + \lambda_L[L - L_M - L_Z] + \lambda_K[K - K_M - K_Z] \quad .$$

From optimality conditions with respect to L_Z and L_M, we find

$$-\frac{1}{\tau} = \frac{L_M \, z \, [\phi_1 + \gamma\sigma L_Z^{\sigma-1} K_Z^{1-\sigma}]}{\alpha} \quad ; \tag{A.4.1}$$

and from optimality with respect to capital allocations we obtain

$$-\frac{1}{\tau} = \frac{K_M \, z \, [\phi_2 + \gamma(1-\sigma) L_Z^{\sigma} K_Z^{-\sigma}]}{(1-\alpha)} \quad . \tag{A.4.2}$$

Using (A.4.1) and then (A.4.2) in the canonical condition for pollution growth, and then using the endowment constraints, we obtain two equations, (3.35) and (3.36), in two unknowns, L_Z and K_Z. Implicit differentiation of both equations with respect to L_Z and K_Z shows that both lines are upward sloping. If the level of capital or labor in abatement increases exogenously, the optimal level of the other factor also increases.

The optimal levels of capital and labor in abatement will be found at the intersection of *LAL* and *KAL*. One condition of intersection is that

$$\textit{slope LAL} \; > \; \textit{slope KAL}$$

$$\frac{\phi_1 L_Z + \gamma\sigma L_Z^{\sigma-1} K_Z^{1-\sigma}[\sigma L_Z + (1-\sigma)L]}{\gamma\sigma(1-\sigma) L_Z^{\sigma} K_Z^{-\sigma}[L - L_Z]} > \frac{\gamma\sigma(1-\sigma) L_Z^{\sigma-1} K_Z^{1-\sigma}[K - K_Z]}{\phi_2 K_Z + \gamma(1-\sigma) L_Z^{\sigma} K_Z^{-\sigma}[(1-\sigma)K_Z - \sigma K]} \quad .$$

Notice that the slope of *LAL* is increasing in ϕ_1, and the slope of *KAL* is decreasing in ϕ_2. Therefore, we can set $\phi_1=\phi_2=0$ and have the following (sufficient) condition for an intersection,

$$(1-\sigma)^2 LK_Z + \sigma^2 L_Z K > -\sigma(1-\sigma)[LK_Z + KL_Z] \quad ,$$

which always holds. Additionally, intersection requires that *KAL* intercepts the L_Z axis below *LAL*. Since there is a positive L_Z intercept for *LAL* but not for *KAL*, this condition also must hold.

For an interior solution for L_Z and K_Z, we must have that the intersection of *LAL* and *KAL* occurs for $L_Z<L$ and $K_Z<K$. We can rewrite (3.35) as a fixed point expression,

$$L_Z = L - \frac{\alpha\rho}{\epsilon[\phi_1 + \gamma\sigma' L_Z^{\sigma-1} K_Z^{1-\sigma}]} \quad ,$$

which we can use to plot L_Z for any given value of K_Z (Figure A.1). Note in Figure A.1 that:

(a) if $L > \frac{\alpha\rho}{\epsilon\phi_1}$, there must be an interior solution for any $K_Z > 0$.

(b) $L > \frac{\alpha\rho}{\epsilon\phi_1}$ is not necessary for $\sigma < 1$, as an interior equilibrium B always exists.

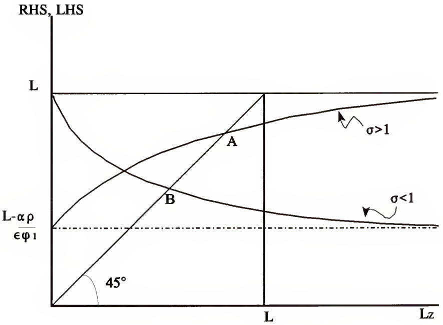

Figure A.1 Conditions for Interior Solutions of L_Z and K_Z

An analogous analysis applies for K_Z, such that

$L > \frac{(1-\alpha)\rho}{\epsilon\phi_2}$. Thus, a sufficient condition for an interior solution is

$$L > \max \left[\frac{(1-\alpha)\rho}{\epsilon\phi_2}, \frac{\alpha\rho}{\epsilon\phi_1} \right] .$$

The comparative statics on the implicit values for abatement labor and capital discussed in Chapter 3 are derived by considering the intersection points [derived from (3.35) and (3.36)] and slopes of *LAL* and *KAL*.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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